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The Light of the Night Sky in EUSO: Duty Cycle and Background

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Abstract

The EUSO detector, which will be installed on the International Space Station, will detect the light produced by the EAS generated by the UHECR when entering the Earth's atmosphere. The EUSO telescope will operate only during dark night. The light background in the EUSO detector is of outmost importance. To determine the detector duty cycle, it is necessary to know the periods in which it will be in the obscurity, taking into account both sun and moon precise ephemerides and the ISS trajectory. For signal to background determination and trigger efficiency study, the photon background has to be evaluated, taking into account the various UV light sources at night: natural sources as airglow, stars and diffuse light of the night sky, and artificial sources.

1. Moonlight background and EUSO duty cycle

Requiring as running condition moonless nights i.e. periods when both the sun and the moon are eclipsed by the earth is a very restrictive decision which reduces the duty cycle to about 12.9%. It is therefore important to define running conditions as a function of the moonlight induced background. We model the incident moonlight flux which mainly depends upon the moon phase angle and estimate the fraction of light reflected upwards.

The moon does not behave as a simple Lambertian spherical reflector. Among other things, it has much stronger phase dependence, shows almost no limb darkening and presents a strong opposition effect. It is therefore unavoidable to use an empirical model fitted to real photometric data that describes both the phase dependence and the absolute luminosity. We use the following phase dependent parametric function of the moon irradiation, which has been shown to fit well recent photometric data at 555 nm [1][2]: $\phi(\alpha) = \phi_0 \times 10^{-0.4\times m(\alpha))}$ where $\phi_0 = 5 \times 10^{-6}\,\mathrm{W/m^2/nm}$ and where the relative magnitude $m(\alpha)$ is given by $m(\alpha) = 1.5|\alpha| + 4.3 \times 10^{-3}\alpha^4$ if α the phase angle is expressed in radians ($\alpha = 0$ is full moon). This flux is further reduced by a factor 0.62 accounting for the relative reflectance of the moon at 350 nm with respect to 555 nm. For our

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purpose of computing low illumination backgrounds it is important to predict the moonlight at large phase angles (near new moon) with some accuracy. The above function drops down to 2.7×10^{-4} of the value of the full moon and according to earthshine measurements, it is expected to slightly overestimate the moonlight flux at large phases.

The reflection of UV light on the earth is mainly due to the atmosphere as will be discussed later. We will consider here the atmosphere as an isotropic diffuser, with a global albedo $A = 0.35$. The background rate per solid angle and per unit surface is thus:
$BG_{moon} = A\phi(\alpha)\, cos(\theta)/2\pi = 2.8 \times 10^5 \times cos(\theta) \times 10^{-0.4 \times m(\alpha)} \gamma/m^2/ns/sr$
where θ is the moon zenith angle.

A detailed simulation of the duty cycle over a one year long period has been performed using 1 minute time steps. We compute the ISS position for each time step using a well established procedure based on the SGP4 model from NORAD [3]. The sun and moon sky coordinates are obtained using routines from the SLAlib package [4], from which we compute the local zenith angle of the moon and the sun as well as the moon phase. We can then define the background condition as above and decide if the current time step is to be considered as live or dead time. The day averaged duty cycle is modulated not only by the moon phase, but also by the fact that the ISS orbit undergoes a precession around the earth pole axis with a period of about 72 days. The orbit polar axis is thus regularly quasi aligned with the direction to the sun or the moon. In such periods, the whole orbit is exposed to the sun or the moon light and the duty cycle may drop to zero for a couple of days. The year average duty cycle with strict zenith angle conditions is 12.9%. Relaxing constrain on the moon allowing it to be above the horizon but asking for a negligible additional background of less than 10 photons/m^2/ns/sr immediately improves the duty cycle up to 18%. Allowing for more background increases the duty cycle slowly up. For example, with 100 photons/m^2/ns which corresponds to 0.15 photoelectrons/pixel/2.5μs, the moon and sun limited duty cycle is 27.3%.

Another positive effect of allowing some moonlight is to decrease the number of very short exposures of duration smaller than the time needed to open and close the telescope shutter. With strict zenith angle conditions, about 10% of the active time consist of openings shorter than 10 minutes. This fraction drops to less than 2% if a $\sim$ 100photons/m^2/ns/sr is used instead.

In conclusion, it seems reasonable to assume a moon and sun limited duty cycle of at least 18% which could increase up to 26% if some additional background is acceptable at the trigger and reconstruction levels.

2. Light of the moonless night sky

Looking at Nadir, EUSO will be sensitive to the light coming from space and upward reflected by the underlying atmosphere and ground. It will be sensitive also to any source of light located below 400 km. Its orbital motion implies that all known source of background around the earth must be considered; the nadir viewing implies that specific conditions of the atmosphere within the field of view should be taken into account.

The sources of photons generating background are numerous. They can be roughly divided in three broad categories : natural night sky diffuse and slowly varying sources, man made sources at ground like city lights, and transient luminous phenomena in lower and upper atmosphere.

The whole sky integrated light from distinct stars has a magnitude of $M \approx -4.5$ in the half hemisphere which contribute at a given time. The planets, if presents, could contribute at a similar level, like Venus with a magnitude of -4.4. The diffuse components of the light of the night sky encompass a variety of physical phenomena over the full range of cosmic scales [5]. In the bandwidth 300-400 nm, three main components contribute significantly to the background. From earth to limbs one observes the Airglow in the upper terrestrial atmosphere, the sun light diffusion and the thermal emission of interplanetary dust (zodiacal light) and the emission by interstellar medium (Integrated faint star light). Other components such as Diffuse Galactic light are small at these wavelengths. The incoming flux on top of atmosphere is around $300\gamma/\mathrm{m}^2/\mathrm{ns}/\mathrm{sr}$ from airglow,$100\gamma/\mathrm{m}^2/\mathrm{ns}/\mathrm{sr}$ from zodiacal light and $80\gamma/\mathrm{m}^2/\mathrm{ns}/\mathrm{sr}$ from faint stars. The total moonless sky light flux on top of atmosphere amount for $510\gamma/\mathrm{m}^2/\mathrm{ns}/\mathrm{sr}$, which corresponds to a magnitude $M \approx 22/Arcsec^2$ in the photometric U Band observed by ground based telescopes.

The Airglow is of special interest since it is an isotropic source of light located in a thin layer at 100 km in the upper atmosphere. This source will be in direct view of EUSO; it contributes also through is reflected part on lower atmosphere. It is then the main source of the nightsky background. The Airglow light comes from atomic de-excitation of oxygen via atom-atom collisions in the upper atmosphere. Three body collisions of atomic oxygen lead to the formation of molecular oxygen in excited state whose decay via Hertzberg transitions contribute in the 300-400 nm band. The production zone comes from the molecular oxygen dissociation by sun radiation, the production maximum occur in a Chapman layer located around 100 km with few km width. The luminosity depends on the solar flux (solar cycle), on the inclination on ecliptic (season and latitude), and on the local density of molecular oxygen at this altitude. The relaxation time of atomic collisions induces a time (longitude) dependence. The real time expectation of the airglow flux along with the ISS trajectory was evaluated from the monoatomic oxygen density from the COSPAR model NRLMSISE-00 [6];

the normalization was taken from ground measurements on June 23rd,1990 at 37N,5E [5]. In short, this flux varies between 250 to 600$\gamma/m^2/ns/sr$.

The total photon background on the entrance pupil of the telescope is the sum of the airglow in direct view plus the incoming night sky flux upward reflected by the atmosphere. The reflected flux depends on the atmospheric optical depth local conditions and on the presence of aerosols. In UV the optical depth of a clear sky is around 0.9 dominated by molecular scattering. A crude estimation of the upward reflected light lead to an atmospheric albedo of 35% and a ground surface contribution of 5% (assuming a surface reflectance of 0.08 for sea). In the presence of cloud (cloud top height at 3km, cloud reflectance of 0.4) the atmospheric reflection above 3km is only 26% while the cloud reflectance contributes to almost 30%. The reflected flux will vary for clear sky (respectively with cloud)in the range 190(260) to 325(450)$\gamma/m^2/ns/sr$. The BABY experiment [7] measured a flux of 300$\gamma/m^2/ns/sr$ above Mediterranean sea.

The total background flux, including the direct view of airglow, will then vary from 440(510) to 925(1050)$\gamma/m^2/ns/sr$. More specific conditions including aerosols and various types of clouds must be accounted for, a more complete estimation is under progress.

3. Light pollution and Transient Luminous Phenomena

Light pollution from human activities were estimated from the photometric world map in V-Band obtained from the OTD satellite observations [8]. They can be converted in U-band according to the spectra of the most commonly used city light lamps. The expectations of bacgkround variations during the telescope survey of the most active regions in the world is in under progress. The Transient Luminous Phenomena such as lightnings is evaluated from the Optical Transient Detector satellite world map data [9]. Upper atmosphere phenomena such as elves,sprites and blue jets, whose description is beyond the scope of the present contribution, are also taken into account since they should contribute to the EUSO duty cycle and background.

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