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Remote sensing of clouds and aerosols with cosmic rays

Andrii Neronov [a,*], Denys Malyshev [a], Anton Dmytriiev [b]

[a] ISDC Data Centre for Astrophysics, Astronomy Department, Geneva University, Ch. d'Ecogia 16, Versoix 1290, Switzerland
[b] Physics Department, Taras Shevchenko National University of Kyiv, Glushkova Av. 2, 03022 Kiev, Ukraine

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ABSTRACT

Remote sensing of atmosphere is conventionally done via a study of extinction/scattering of light from natural (Sun, Moon) or artificial (laser) sources. Cherenkov emission from extensive air showers generated by cosmic rays provides one more natural light source distributed throughout the atmosphere. We show that Cherenkov light carries information on three-dimensional distribution of clouds and aerosols in the atmosphere and on the size distribution and scattering phase function of cloud/aerosol particles. Therefore, it could be used for the atmospheric sounding. The new atmospheric sounding method could be implemented via an adjustment of technique of imaging Cherenkov telescopes. The atmospheric sounding data collected in this way could be used both for atmospheric science and for the improvement of the quality of astronomical gamma-ray observations.

1. Introduction

Knowledge of optical properties of clouds and aerosols is important in a wide range of scientific problems, from atmospheric and climate science [1] to astronomical observations across wavelength bands [2–4].

Clouds are reflecting and absorbing radiation form the Sun, thus regulating the intake of the Solar energy by the Earth. Study of scattering and absorption of light by clouds is, therefore, a key element for understanding of the physics of the Earth atmosphere [1,5]. Aerosols work as condensation centres for formation of cloud water droplets and ice crystals. Understanding of relation between clouds and aerosols is one of the main challenges of atmospheric science [1,6].

Probes of the properties of clouds and aerosols are done using in situ measurements and remote sensing techniques [7] including imaging from space or from the ground [8], observations of transmitted light from the Sun or Moon [9] and sounding of the clouds with radiation beams [10]. LIght Detection And Ranging (LIDAR) sounding techniques (Fig. 1) probe vertical structure of clouds and aerosols via timing of backscatter signal from a laser beam [10].

Presence of clouds perturbs astronomical observations in the Very-High-Energy (VHE) γ-ray (photons with energies 0.1–10 TeV) band and operation of Cosmic Ray (CR) experiments which use the Earth atmosphere as a giant high-energy particle detector [3,4]. Imaging Atmospheric Cherenkov Telescope (IACT) arrays,[1] as well as air fluorescence telescopes for detection of Ultra-High-Energy CRs[2] detect cosmic high-energy particles via imaging of Cherenkov and fluorescence emission from the particle Extensive Air Showers (EAS), initiated by the primary cosmic particles. Information on the presence and properties of the clouds and aerosols is essential for the proper interpretation of the data collected in this way. Gamma-ray/CR observations affected even by optically thin clouds are normally excluded from data sets, because the properties of the clouds are not known sufficiently well to allow correction for the effects of scattering of light by the atmospheric features.

Here we show that Cherenkov light produced by the EAS could be used as a tool for remote sensing of the atmosphere. We show that this tool allows characterisation of three-dimensional cloud/aerosol coverage above the observation site and provides information on physical properties of cloud and aerosol particles.

2. The remote sensing method

CRs of energy $E > E_{cr}$ are hitting the atmosphere from all directions at a rate [11] $N_{cr}(E_{cr}) \sim 10[E_{cr}/100\text{GeV}]^{-\gamma_{cr}+1}$ $(\text{m}^2\ \text{s sr})^{-1}$ where $\gamma_{cr} \simeq 2.7$ is the slope of the CR spectrum. Each CR induced EAS generates a short flash of visible-to-UV light via Cherenkov

[1] HESS telescopes: http://www.mpi-hd.mpg.de/hfm/HESS/; MAGIC telescopes: https://magic.mpp.mpg.de; VERITAS telescopes: http://veritas.sao.arizona.edu.

[2] Pierre Auger Observatory: http://www.auger.org; Telescope Array: http://www.telescopearray.org; JEM-EUSO: http://jemeuso.riken.jp/en/.

* Corresponding author. Tel.: +41 223792120.
E-mail address: Andrii.Neronov@unige.ch (A. Neronov).

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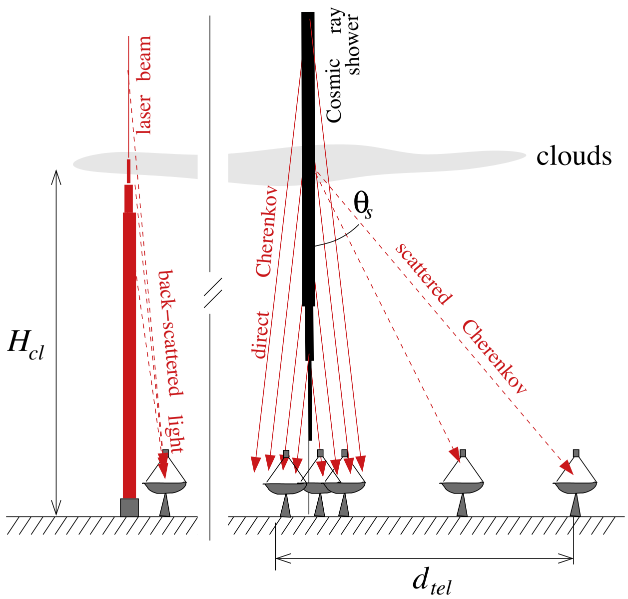

Fig. 1. Principle of remote sensing of the atmosphere with Cherenkov light beams of EAS (right) shown in comparison with the scheme of operation of LIDARs (left).

and fluorescence mechanisms. The entire set of EAS provides a source of light distributed everywhere throughout the atmospheric volume. This light source is well calibrated since the CR flux is well measured and is almost invariable in time at the energies above 100 GeV [11]. Techniques for detection of light flashes from EAS are nowadays well developed and are widely used in γ-ray astronomy [12] and CR research [13]. It is, therefore, natural to consider a possibility to use the light from EAS for the study of the atmosphere.

The suggested principle of remote sensing of the atmosphere with EAS light is shown in Fig. 1. The EAS is observed from the ground by a system of (minimum two) telescopes. Stereo vision technique enables reconstruction of three-dimensional geometry of the EAS and measurement of the number of photons from each EAS as function of altitude, dN_γ/dH. Measurements for individual EAS are combined into a cumulative vertical profile $dN_{\gamma,cum}/dH(x,y,H)$ of emission from a large number of EAS. It is a function of the three-dimensional position in the atmospheric volume, (x,y,H) within the Field-of-View (FoV) of the telescopes. Scattering and absorption of light by atmospheric features leads to the distortion of the cumulative vertical profile. Characterisation of these distortions provides a tool for the measurement of the distribution and optical properties of the features.

3. Vertical profile of Cherenkov light in clear and cloudy sky

High-energy particles forming an EAS move with velocities faster than the speed of light in the atmosphere. Superluminal motion is accompanied by emission of Cherenkov radiation at a known rate Y_{Ch} [14]. The number of high-energy particles in the EAS is, on average, also a known function $N_p(E_{cr},X)$ of the atmospheric column density along the EAS track, X [15]. The overall flux of Cherenkov light from the EAS is the sum of emission from all the particles, $dN_{Ch}/dX(E_{cr},X,\alpha,\lambda) = Y_{Ch}N_p(E_{cr},X)$. It depends on the photon wavelength, λ and on the angle between the EAS axis and photon direction, α. Cherenkov photons are concentrated in a narrow beam with approximately exponential profile $dN_{Ch}/dX \sim \exp(-\alpha/\alpha_c)$, where $\alpha_c \sim 1 degr$ is a cut-off angle determined by the angle of Cherenkov emission in the air and by the angular spread of high-energy particles [16]. Linear brightness profile of EAS as a function of altitude H is $dN_{Ch}/dH = (\rho/\cos\theta_z)dN_{Ch}/dX$ where ρ is the atmospheric density and θ_z is the zenith angle of the EAS. In our illustrative example we consider observations in Zenith direction, $\theta_z \simeq 0^\circ$.

Attenuation of visible and UV light during propagation through the atmosphere determines the number of photons N_γ reaching the telescope

$$\frac{dN_\gamma}{dH} = \frac{dN_{Ch}(H,\alpha(H),\lambda)}{dH}\exp\left(-\tau(H,\lambda)\right) \quad (1)$$

where the $\alpha(H)$ is the angle at which the EAS track is visible from the location of the telescope. The optical depth τ is determined by the density n_s and extinction cross-section σ_s of the scattering centres, $\tau = \int_{H_{tel}}^{H}\sigma_s(\lambda)n_s/\cos(\alpha)dh$ where H_{tel} is the altitude of the telescope.

Vertical profiles of individual showers are shaped by a random process of collisions between the high-energy particles and air molecules. They exhibit strong shower-to-shower fluctuations. However, stacking of the vertical profiles of a large number of EAS removes the fluctuations. EAS signal is detected on top of random fluctuations of the Night Sky Background. With typical reflector sizes $D_{tel} \sim 4$–30 m, currently existing IACTs are able to detect the EAS initiated by CRs with energies above the energy threshold E_{thr} of several hundred GeVs hitting the ground within an area $A_{eff} \sim 10^5$ m^2 around the telescope [12]. This provides a rate of detection of EAS $\mathcal{R}_{cr} = N_{cr}(E_{thr})A_{eff} \sim 1\,[D_{tel}/10\text{ m}]^{2(\gamma_{cr}-1)}$ kHz, where we have assumed that the energy threshold scales approximately as the telescope aperture $E_{thr} \sim D_{tel}^{-2}$. Each particular EAS triggers the readout system of the telescope if it produces more than $N_{\gamma,min} \sim 10$–10^2 photon counts in the telescope camera. The statistics of Cherenkov signal from all the EAS accumulated each second is rather high, $\mathcal{R}_{cr}N_{\gamma,min} \sim 10^5[D_{tel}/10\text{ m}]^{2(\gamma_{cr}-1)}$ ph/s.

Presence of an atmospheric feature (cloud or aerosol layer) of an optical depth τ_{cl} distorts the cumulative vertical profile in several ways. First, it reduces the number of Cherenkov photons reaching the telescope from behind the feature by $\exp(-\tau_{cl})$. Next, it increases the energy threshold by up to $\exp(\tau_{cl})$, depending on the altitude of the feature. This is due to the fact that the telescope detects only EAS which produce $N_{\gamma,min}$ photon counts in the camera. Higher energy of EAS triggering the telescope is needed to compensate the loss of photons from behind the cloud. Finally, scattering of Cherenkov light in the cloud increases the signal from the altitude of the cloud and facilitates detection of the signal at large off-axis angles α, thus imitating an increase of the telescope's FoV. Photons which would miss the telescope in the absence of the cloud, could occasionally be scattered in the direction of the telescope and in this way contribute to the EAS image, as shown in Fig. 1. For moderately optically thick clouds, light propagation in the cloud is dominated by single scattering events. Scattered light signal arriving in the telescopes at a distance d_{tel} from the EAS footprint is proportional to the differential cross-section of scattering $d\sigma_s/d\Omega(\theta_s)$ (or, equivalently, scattering phase function) at an angle $\theta_s = \arctan(d_{tel}/H_{cl})$. In the absence of absorption of light (good approximation in the UV band) the altitude-dependent number of scattered photons reaching a telescope of aperture A_{tel} is

$$\frac{dN_\gamma}{dH} = N_{Ch}\left(n_s\frac{d\sigma_s}{d\Omega}\bigg|_{\theta_s}\frac{A_{tel}\cos^2\theta_s}{H_{cl}^2}\right)\exp\left(-\int_{H_{tel}}^{H_{cl}}\frac{\sigma_s n_s}{\cos\theta_s}dh\right) \quad (2)$$

where

$$N_{Ch}(H) = \int_{H_{cl}}^{\infty}\int_{\Omega}\frac{dN_{Ch}}{dH}\exp\left(-\int_{H_{cl}}^{h}\sigma_s n_s dh'\right)d\Omega dh \quad (3)$$