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Measurement of the angular distribution of Čerenkov light in ultra-high-energy extensive air showers

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Abstract. We report on a direct measurement of the angular distribution of Čerenkov light in extensive air showers with energies greater than 10^{17} eV. The measurement is performed by viewing sections of showers simultaneously at different emission angles with two Fly's Eye detectors. The data imply a value of the multiple scattering parameter $\theta_0 = 4.0 \pm 1.2°$ for threshold energies between 20 and 60 MeV.

1. Introduction

We report on a direct measurement of the angular distribution of Čerenkov light in extensive air showers (EAS) with energies greater than 10^{17} eV. The measurement, described below, is performed by viewing EAS sections simultaneously at two different emission angles with two Fly's Eye detectors situated 3.5 km apart. The detectors are described in detail in [1]. Briefly, they consist of 67 (FE I) and 8 (FE II) 1.5 m diameter mirrors. Each mirror has 12 or 14 phototubes located at its focal plane. Each phototube observes a $\pm 2.5°$ section of the sky. The tubes in FE I subtend the entire hemisphere of the sky, while FE II observes an 80° azimuthal and 45° zenith angle segment.

As an EAS develops in the atmosphere above the Fly's Eyes, the nitrogen scintillation and Čerenkov light produced are detected by the phototubes and the amplitude and relative time of arrival of the resultant charge are digitised. For the data considered here, the EAS is viewed in stereo by both eyes and the zenith, azimuthal and ground impact coordinates can be determined through knowledge of the viewing directions of the phototubes that detected the light. The typical measurement errors on the zenith and azimuthal angles are $\sim 1.5°$. Once the geometry is known, the number of ionising particles in the shower segment viewed by a tube can be reconstructed using the calibrated response of the system to light in the 2800–4000 Å wavelength interval.

Figure 1 shows that, for showers viewed in stereo, each track segment will be viewed at two different emission angles by FE I and II. When the EAS is viewed at small emission

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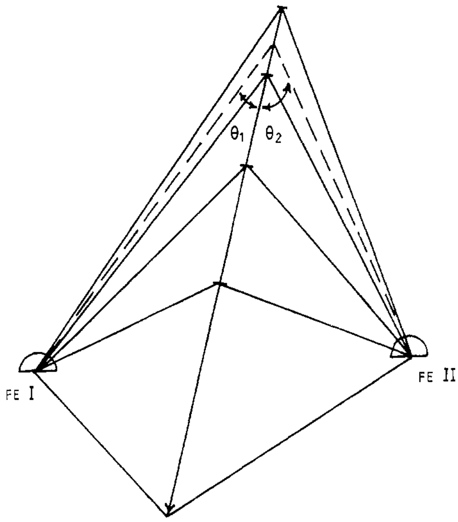

Figure 1. Geometry of EAS detection. The axis of the EAS is indicated by the arrow. θ_1 and θ_2 are the emission angles with respect to FE I and FE II for the first bin.

angles (<20°), the contribution of Čerenkov light is expected to dominate by more than an order of magnitude and the scintillation light can be neglected.

2. Angular distribution of Čerenkov light

The angular distribution of Čerenkov light in an EAS is expected to be entirely related to the angular distribution of particles in the EAS. The multiple scattering problem for a single particle travelling through a medium has been analysed in detail by Bethe [2]. The Bethe formalism, in addition to the usual gaussian part, includes the contribution of large-angle single scattering. Several authors have incorporated the Bethe formalism into a Monte Carlo study of the angular distribution of particles in EAS as a function of shower development [3, 4]. In addition, Hillas [5] has used a combination of gaussian multiple scattering and Rutherford scattering for the large-angle contribution in a separate Monte Carlo calculation. The results of these studies show that the angular distribution of ionising particles averaged over the length of the EAS can be well represented by

$$\frac{dN}{d\Omega} \propto \frac{\exp(-\theta/\theta_0)}{2\pi\theta_0 \sin\theta}$$

where θ is the emission angle relative to the EAS axis and θ_0 is a function of the threshold energy for Čerenkov light emission E_T. E_T (in MeV) is related to the index of refraction n

Table 1. Parametrisation of θ_0 dependence on E_T (E_T in MeV and θ_0 in radians). $\theta_0 = aE_T^{-b}$.

Reference	a	b
[3]	0.83	−0.67
[4]	0.77	−0.65
[4, 5]	0.85	−0.66

of the atmosphere at the height of emission through the relation $E_T = 0.511[2(n-1)]^{-1/2}$. The functional dependence on the threshold energy has been parametrised for the three calculations by the authors of references [3] and [4] in the form $\theta_0 = aE_T^{-b}$ and is given in table 1. These calculations also indicate that the dependence of θ_0 on longitudinal shower development is small.

3. Measurement of θ_0

We perform a measurement of θ_0 using the following technique. The EAS is assumed to be a line source of light. Light arriving at FE I from the EAS is rebinned in angular bins of fixed width (6°). The first bin represents light emitted by the EAS at a mean emission angle of 3°, the second light at 9° and so on. As can be seen from figure 1, these bins define track segments along the EAS axis. We define angular bins with respect to FE II such that these bins view the same track segments defined above. For light emitted isotropically, the photoelectron yields for each track segment corrected for atmospheric attenuation and solid-angle effects must be the same in FE I and FE II if there are no reconstruction errors. Figure 2 shows the ratio of FE II to FE I corrected light yields for segments viewed with emission angles greater than 40° by both FE I and FE II. For these segments, the Čerenkov light contribution is negligible and isotropic scintillation light dominates.

For small emission angles, the yields due to direct Čerenkov light will have the relation

$$\frac{L_2 \sin\theta_2}{L_1 \sin\theta_1} = \exp[-(\theta_2 - \theta_1)/\theta_0] \tag{1}$$

where L is the corrected light yield and θ_1 and θ_2 are the emission angles with respect to FE I and FE II. Observation of a proportionality between ln $(L_2 \sin\theta_2 / L_1 \sin\theta_1)$ and $\Delta\theta$ will thus yield a measurement of θ_0.

As the EAS develops, an intense beam of Čerenkov light is produced along its axis and Rayleigh and Mie scattering will produce scattered Čerenkov light with an angular distribution different from that given in equation (1). To minimise this problem, we cut on track segments which correspond to an EAS longitudinal development parameter η of less

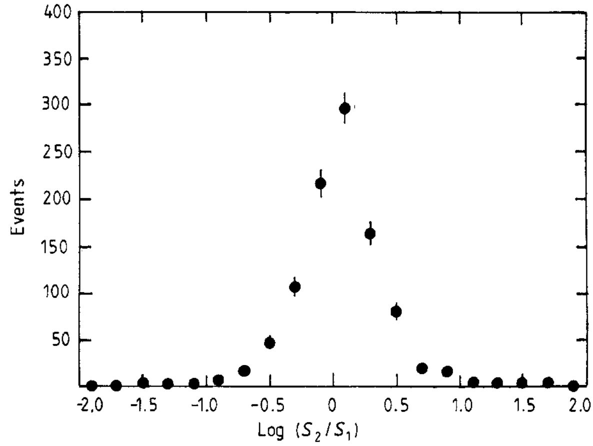

Figure 2. Ratio of sizes of segments viewed by FE I and FE II at greater than 40°.

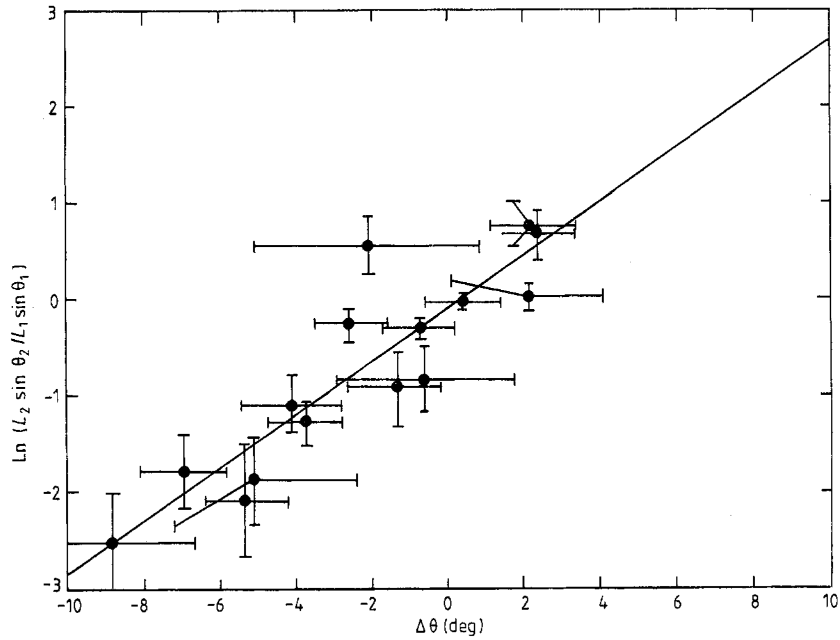

Figure 3. Distribution of ln (L_2 sin θ_2/L_1 sin θ_1) against $\Delta\theta$ for segments with age less than 0.4 and emission angles less than 20°. The straight line is the best fit to the data.

than 0.4. This parameter is defined as the ratio of the size of the shower segment to the size of the shower at shower maximum. Shower segments beyond the shower maximum have $\eta > 1.0$. The contribution of Rayleigh- and Mie-scattered Čerenkov light to segments with $\eta < 0.4$ is expected to be small.

The total number of EAS observed in stereo is 278. Figure 3 shows the data for 15 track segments surviving η cuts of less than 0.4 and emission angle cuts of less than 20°. For these data, we also demand that the uncertainty in both emission angles and the difference in emission angles be less than 3°. A clear linear relation between emission angle difference and light yield ratios is observed. The slope of a linear fit using the effective variance method [6] yields $\theta_0 = 4.0 \pm 1.2°$.

In principle one should integrate the differential Čerenkov light yield over the angular range of each bin. We have checked that for $2 < \theta_0 < 6°$ and typical emission angles of 10–15° our neglect of this integration does not affect our conclusions.

The threshold energy for these bins runs from 20 to 60 MeV and is tightly clustered around 34 MeV. The predicted value of θ_0 for this average threshold energy ranges from 4.4 to 4.8° in good agreement with the data.

A lack of statistics precludes the study of the dependence of θ_0 on E_T for larger values of E_T. This awaits the completion of a larger FE II with 36 mirrors.

Acknowledgment

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