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Zenith Angle Dependence of the Response of Cherenkov Telescopes

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Abstract

The variation of the amount of light detected from Cherenkov flashes with zenith angle is a result of the interaction of shower particles with air and the attenuation of the Cherenkov light generated by these particles. It is important to determine the effect of zenith angle on Cherenkov light to get information about its influence on the particle density at VHE. The response function of the visible and UV cameras with and without UV filters is calculated. The variation of the response of the different cameras with zenith angle has been characterized. The results suggest a possible use of the UV camera with the filter at large zenith angles as a muon detector. The attenuation length of VHE shower particles is estimated to be in the range 840—1060 g/cm^2.

1 The Response Function

The response function of an atmospheric Cherenkov telescope (H) includes the Cherenkov light spectrum generated by shower particles, the atmospheric transmittance (T_a) between the altitude at which the Cherenkov light is generated and the observing elevation, and the instrumental parameters; PM quantum efficiency (ε), mirror reflectivity (R) and filter transmission (T_f). It is the integration of the variable $\eta(\lambda,\theta)$ for the range of wavelengths at which the camera is sensitive (Badran, 1997). The variable η is defined as;

$$\eta(\lambda,\theta)=T_a(\lambda,\theta).R(\lambda).\varepsilon(\lambda).T_f(\lambda)/\lambda^2$$

Fig. 1 shows the dependence of the response function on the altitude at which Cherenkov light is generated and a telescope at 2.3 km observation level. The zenith angles are calculated up to 75° because observations at large zenith angles have proven their usefulness (Tanimori *et al.*, 1994 and Krennrich *et al.*, 1995).

Two filters were suggested for both the visible (Bi Alkali PM) and UV solar-blind (CsTe photocathode on quartz window) cameras (Badran *et al.*, 1997a). A Co-Ni filter (F1) was used with the visible camera in a successful detection of the Crab nebula (Chantell *et al.*, 1997), while a Co-Ni-dye filter (F2) was specially developed for UV camera of the ARTEMIS experiment (Urban *et al.*, 1990); this enabled the camera to be pointed close to the full moon (Badran *et al.*, 1997b). The response of the two cameras with the addition of the filters is also shown in Fig. 1.

The response function drops as the elevation of the generation level of the Cherenkov light increases. This drop increases with the increase of zenith angle. The UV camera is more sensitive to the variation of the zenith angle than the visible camera. The addition of either filter also increases the sensitivity of the two cameras to the variation of both zenith angle and the Cherenkov light altitude.

Clearly, most of the light collected by the UV camera with or without F2 is emitted close to the telescope. This would suggest that the UV camera with F2 can be used in low elevation angle measurements as a good muon detector. At 75° the relative response function for 4 and 9 km elevation drops to about 1% and 0.01%, respectively, of its value for 3 km elevation and vertical incidence. Such measurements would make the telescope sensitive to the light generated very close to the observation level. The telescope response for these measurements should be relatively stable with changes of atmospheric conditions (Badran, 1999).

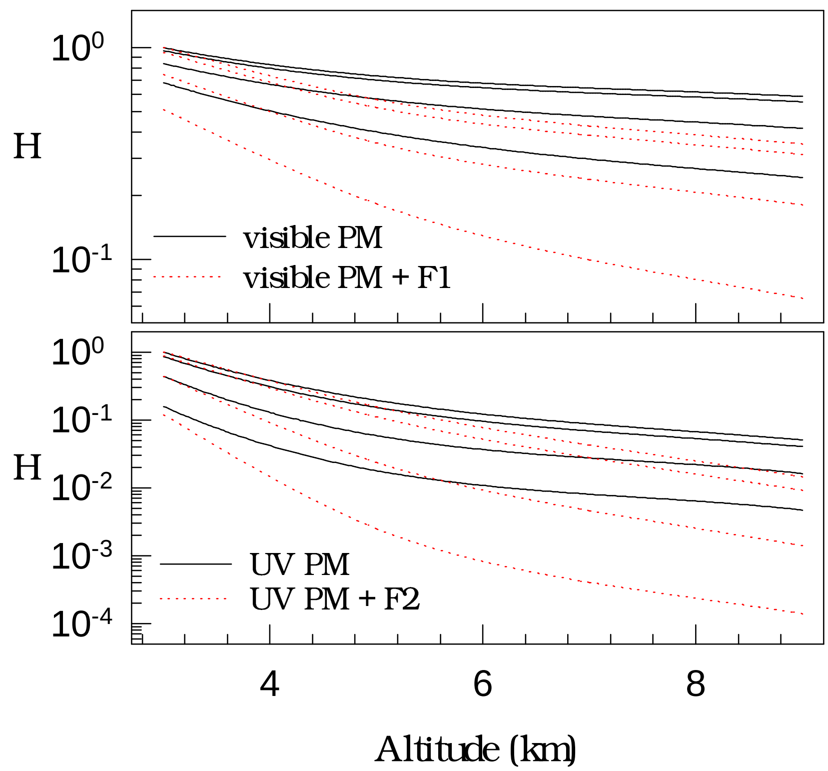

Fig. 1. Variation of the response function with the altitude at which the Cherenkov light is generated for the visible (up) and UV (down) cameras without (solid line) and with (dotted line) the corresponding filter. The observing latitude is 2.3 km and the zenith angles are 0, 30, 60, and 75°.

2 Zenith Angle Distribtion

The zenith angle distribution of UHE showers has been investigated to study the physics of shower development, to check the array performance, to estimate the vertical intensity of the primary flux, to extract the inelastic cross section of p-air collision (Hara et al., 1983), and to search for a possible correlation between the distribution and the primary particle composition (Cimpa and Clay, 1998).

One way to represent the relation between the frequency of UHE showers and the zenith angle is an exponential formula in the form $\exp[-t_o(\sec\theta - 1)/\Lambda]$, where t_o is the vertical depth of the experiment, and Λ is interpreted as the attenuation length of EAS. An alternative formula is the cosine power formula given by $\cos^n\theta$, where $n \approx t_o/\Lambda$.

The optical detection of cosmic ray showers is an important technique in studies of VHE gamma-ray sources. Cherenkov light emission in air is nearly straight forward along the charged particle's path. Therefore, the main factor contributing to the zenith angle distribution of the Cherenkov light flashes is that of shower particles.

For the attenuation of Cherenkov light, a comparable formula can be used in the form $\exp[-\mu(t_o - t_C)(\sec\theta - 1)]$, where t_C is the vertical depth at which the Cherenkov light is generated and μ is the linear attenuation coefficient of the Cherenkov light. The values of the calculated linear absorption coefficient are listed in Table 1 for different elevations (θ=0—75°). The overall zenith angle dependence of the trigger rate can also be considered to have the form $\cos^{n+m}\theta$; where the parameter m represents the variation of Cherenkov light with zenith angle. The cosine power formula does not quite fit the present data in the range 0–75°. Instead it provides a good representation of the data in the range 0–50°. The values of the parameter m for both the visible and UV cameras are given in Table 2.

Table 1. The linear absorption coefficient (km^{-1}) calculated using the exponential formula of zenith angle dependence (θ=0–75°) for visible and UV photomultipliers with and without the corresponding filter.

Elevation (km)	Visible PM		UV PM	
	without filter	with filter F1	without filter	with filter F2
3	0.19	0.34	0.91	1.06
5	0.08	0.14	0.30	0.53
7	0.06	0.11	0.18	0.36
9	0.05	0.09	0.12	0.34

Table 2. The calculated values of the parameter m in the cosine power formula of zenith angle (θ=0–50°) for visible and UV photomultipliers with and without the corresponding filter.

Elevation (km)	Visible PM		UV PM	
	without filter	with filter F1	without filter	with filter F2
3	0.24	0.40	1.06	1.09
5	0.33	0.63	1.61	2.57
7	0.40	0.76	1.67	3.12
9	0.45	0.86	1.68	3.30

The experimentally measured value for n+m for the trigger rate of the Whipple 10m telescope was found to be 0.9 (Cawley *et al.*, 1990). This value is naturally for showers with light generated at different elevations above the observing level and should also depend on the triggering condition. Taking into account this value and the calculated values of m for different elevations, the expected value for n that represents only the attenuation of the shower particles is in the range 0.45–0.66. This would lead to an attenuation length of VHE shower particles in the range Λ=840—1060 g/cm^2. This result is about one order of magnitude greater than the measured values for EAS in the energy range above 10^{14} eV (Badran, 1993). A careful experimental study would lead to a more precise result based on the estimated effect of zenith angle on Cherenkov light.

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