Space-angular and temporal parameters of Cherenkov light emission in air showers of energy from 1 TeV down to 10 GeV

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Abstract

Recently, ground based very high energy γ-ray astronomy, using the Cherenkov light imaging technique, has demonstrated a great success in clearly detecting and also studying the energy spectra and time variations of a several γ-ray sources in a quite wide energy range from 200 GeV up to 15 TeV. It is important to note that most of the Monte Carlo predictions concerning this technique made in the past, for instance the cosmic ray rejection power, angular and energy resolution for the γ-ray-induced showers and in particular regarding the simultaneous stereoscopic observations by more than one telescopes have been proved by the currently operating instruments.

The future development of this technique is mainly associated with the further reduction of the energy threshold down to 50-100 GeV or even to 10 GeV to fill the gap between the satellite and ground based observations. The design and performance of the future "sub 100 GeV" detectors have to be studied by means of relevant Monte Carlo simulations beforehand. In this paper the attempt is undertaken to understand how reliable are the current Monte Carlo predictions regarding the basic characteristics of the Cherenkov light (lateral, temporal and angular distributions) in air showers, in particular γ-ray-induced showers, of energy $\geq$ 100 GeV, as well as how these characteristics behave at much lower energies 10-100 GeV.

1. Introduction

For the first time Blackett (1949) suggested that the Cherenkov light emission produced by the cosmic ray (CR) particles in the Earth's atmosphere gives a significant contribution to the integral light flux from the night sky. Galbraith & Jelley (1953, 1955) predicted a possibility to observe Cherenkov light flashes from the extensive air showers (EAS) initiated by energetic cosmic ray particles and later confirmed it using a quite simple experimental technique.

The idea to detect Cherenkov light flashes from EAS comes from simple physics reasoning. Primary cosmic rays of a high energy entering the atmosphere produce a cascade of the secondary charged particles having their energy well above the energy threshold of Cherenkov light production. The EAS particles arrive at the Earth's surface in $\simeq 10^{-8}$ sec that makes it possible to measure the Cherenkov light emission from the EAS within the exposure time of 10-30 nsec. The amount of the night sky light detected for such short time intervals appears to be negligible compared with Cherenkov light flashes from the EAS having enough energy if the optical reflector used has a sufficient mirror area. Increasing the mirror area of the optical reflector and also using multichannel fast electronics one can get more Cherenkov light from

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the EAS against the night sky background and consequently decrease the energy threshold of the detector.

Since 1955 when the first measurements of the Cherenkov light flashes from air showers have been performed tremendous progress happened in developing the registration technique. Currently operating ground based imaging air Cherenkov telescopes, successfully used for the observations of very high energy γ-rays, have already reached the energy threshold of $\simeq 200$ GeV (e.g. Weekes, 1996). In general, the future development of this technique is associated with the further reduction of the energy threshold. Thus the forthcoming instruments (HESS, MAGIC, VERITAS) are expected to have an energy threshold around 50-100 GeV or even less. At the same time another technique used to detect the Cherenkov light from air showers with a large array of the single mirrors widely distributed at the observation level (CELESTE, Mini-GRAAL, STACEE) is anticipated to be effective for registration of γ-rays of energy as low as 10 GeV.

For understanding the performance of future *low energy* (or "sub 100 GeV" class) detectors relevant Monte Carlo simulations are needed. Here an overview is given for the space-angular and temporal characteristics of Cherenkov light emission from air showers induced by primary γ-rays of energy 10-100 GeV. For that detailed Monte Carlo simulations have been carried out using the *Altai* Monte Carlo Code. The calculated characteristics of the Cherenkov light were compared with other simulations and a critical analysis is made. Study of the difference of 10 GeV γ-ray-induced air showers and the background cosmic ray air showers of around 100 GeV is out of the frame of this particular paper and is actually the topic of another forthcoming paper.

2. Total amount of the Cherenkov light photons

In respect of the Cherenkov light emission from EAS the Earth's atmosphere could be considered as a huge calorimeter used to detect air showers. The measured Cherenkov light comes from showers cascading very far from the observation level. However the number of Cherenkov photons hitting the optical detector even with a modest mirror size is large enough to get the energy threshold of the registered showers as low as 1 TeV.

An estimate of the number of emitted Cherenkov light photons in the γ-ray-induced air shower, Q_{ph}, could be made analytically in the following way. The emissivity of Cherenkov light photons from the unit path length [cm] of a cascade electron according to Frank & Tamm (1937) is given by:

$$\frac{dQ_{ph}}{dl} = 2\pi\alpha(\frac{1}{\lambda_1} - \frac{1}{\lambda_2})sin^2\Theta_c \tag{1}$$

where Θ_c denotes the angle of the Cherenkov light emission in respect to the electron's track. Assuming that the energy of the emitting cascade electrons is much higher the energy threshold of the Cherenkov light production in atmosphere ($\beta \simeq 1$) the angle Θ_c is calculated (e.g. Jelley (1965)) as

$$\Theta_c^2 = 2\eta,\ \eta = (1-n) = \eta_0 \cdot e^{-h/\lambda},\ \eta_0 = 2.93 \cdot 10^{-4},\ \lambda \simeq 7.1\,\mathrm{km} \tag{2}$$

where h is a height [km] above the sea level and n is a refractive index in the atmosphere at this height. One can rewrite Eqn. (1) using Eqn. (2) in a form

$$dQ_{ph}/dl \simeq 2Q_0 \cdot \eta_0 \cdot e^{-h/\lambda},\ Q_0 = 2\pi\alpha(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}) \tag{3}$$

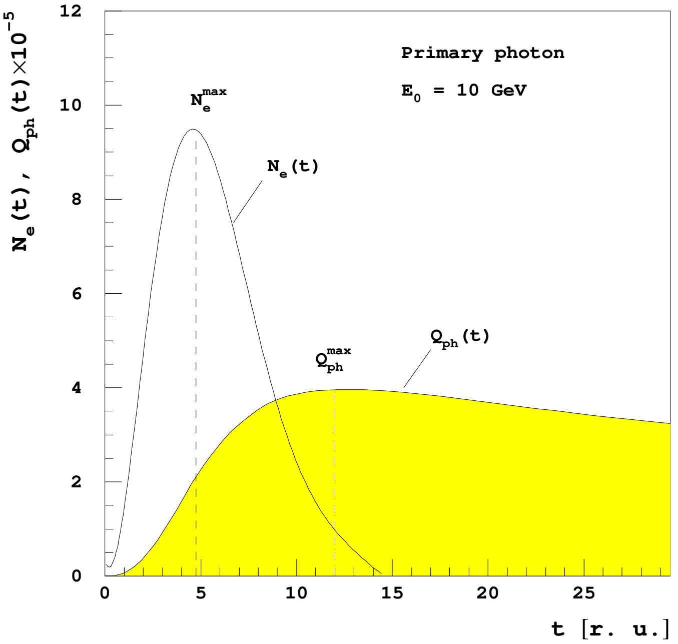

Fig. 1: An average number of Cherenkov light photons, $Q_{ph}(t)$, and cascade electrons, $N_e(t)$, in 10 GeV γ-ray-induced air shower at different atmospheric depthes, t.

To calculate the total number of Cherenkov light photons emitted in an air shower one has to integrate over the depth of the cascade development measured in radiation units (t_0)

$$Q_{ph} = 2Q_0 \cdot (\frac{\eta_0 t_0}{\rho_0}) \int N_e(t)dt \qquad (4)$$

In air, the primary energy of air electromagnetic cascade, E_0, is related to the total path length of the cascade electrons according to Rossi & Greisen (1941) as

$$E_0 = \epsilon_0 \int N_e(t)dt, \;\; \epsilon_0 = 78 \text{ MeV} \qquad (5)$$

Finally the total number of Cherenkov photons emitted in an electromagnetic cascade developing in the atmosphere could be estimated as

$$Q_{ph} = 2 \cdot Q_0(\frac{\eta_0 t_0}{\rho_0})(\frac{E_0}{\epsilon_0})\delta \qquad (6)$$

where δ denotes the part of the cascade electrons above the energy threshold of the Cherenkov light production in air. Note that Eqn. (6) does not take into account the absorption of the Cherenkov photons.

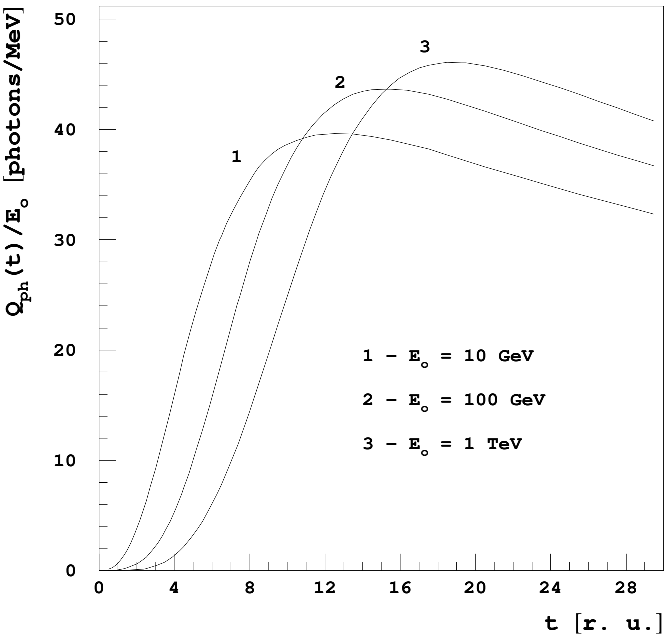

Fig. 2: An average number of Cherenkov light photons, $Q_{ph}(t)$, in 10 GeV, 100 GeV and 1 TeV γ-ray air shower at different depthes of cascade development (Monte Carlo simulations).

From Eqn. (6) for an electromagnetic cascade of primary energy E_0 = 10 GeV ($\delta \simeq 0.25$) the total number of Cherenkov photons emitted in the wavelength range $\Delta\lambda = (0.3 \div 0.6)\mu$m is about $Q_{ph} \simeq 4.0 \cdot 10^5$ [photons].

The function $Q_{ph}^{\gamma}(t)$ (where t is a depth along the shower axis in radiation length) averaged over the sample of the Monte Carlo simulated air showers initiated by primary photons of energy 10 GeV is shown in Figure 1. Increase in the number of electrons with the depth leads to rapid growth of the number of emitted Cherenkov light photons up to the depth $\simeq$ 5 r.u. where the electromagnetic cascade has its maximum, N_e^{max}.

Assuming that absorption of the Cherenkov light photons is small enough at the scale of 10 GeV shower development depth (approximately $\simeq$ 12 r.u.), the number of the Cherenkov light photons in a peak, Q_{ph}^{max} (see Figure 1), is equivalent to the total number of photons emitted in shower. It decreases further on with the atmospheric depth due to the absorption (see Figure 1). One can see the analytical estimate derived above is in a good agreement with the results of the Monte Carlo simulations.

From Eqn. (6) the total number of Cherenkov photons is proportional to the primary energy of the electromagnetic cascade, $Q_{ph} \propto E_0$. The results of the Monte Carlo simulations on the average functions $Q_{ph}(t)$ for the different energies of a primary γ-rays are shown in Figure 2. Note that the decrease in the Cherenkov light flux due to the atmospheric absorption is around 20 %. The small increase in Q_{ph}/E_0 with E_0 comes from the change of δ (see Eqn. (6)) as well as from the slight energy dependence of the Cherenkov light emissivity on the energy of the cascade particles ignored in Eqn. (2). The total amount of Cherenkov photons from a γ-ray-induced air shower at sea level derived from the Monte Carlo simulations could be represented by

$$Q_{ph}^{\gamma} = (28 + 4 \cdot lg(E_0)) \cdot E_0 \cdot 10^3 \quad (7)$$

where E_0 is the primary energy of a shower in GeV.

3. The lateral distribution function

The first simple calculations of the lateral distribution of the Cherenkov light in the electromagnetic air shower were done by Galbraith & Jelley (1953). In these calculations the Coulomb scattering of the cascade electrons was neglected and all electrons were assumed to produce Cherenkov light emission with the same efficiency ($\beta \simeq 1$). Under such assumptions, Galbraith & Jelley (1953) gave a formula for the radius of the Cherenkov light-cone at sea level in dependence on the height of emission

$$r = (5.8 \cdot 10^{-4})^{1/2} h \cdot exp(-h/2\lambda) \ \ [\mathrm{m}] \quad (8)$$

It has a maximum value at $r \simeq 126$ m for the light coming from the height $h_{max} = 2\lambda = 14$ km above the sea level. Galbraith & Jelley (1953) claimed for the first time on existence of a peculiarity (hump) in the lateral distribution of the Cherenkov light photons at the radius from the shower axis $r \simeq 120 - 140$ m and rapid decrease in the photon density beyond the distance 140 m from the shower core.

More precise calculations taking into account the Coulomb scattering of the electrons have been performed by Goldanskii & Zhdanov (1954). They derived analytical formulas for the Cherenkov light contribution from different heights above sea level to the detector located at different impact distances from the shower core up to 1 km. It was noted for the first time that the Cherenkov light intensity at sea level could be considered as a superposition of two components (a) *direct* emission from the high energy electrons moving along the shower core when the following relation is valid, $\Theta_c > \langle\Theta_s\rangle$, where $\langle\Theta_s\rangle$ is the mean-squared angle of the electron scattering and (b) *diffuse* emission from the low energy electrons characterized by the condition $\Theta_c < \langle\Theta_s\rangle$. The *direct* emission mostly contributes at the distances from the shower core $r \simeq 100 - 140$ m whereas the *diffuse* emission generated at greater ages of the shower development in denser layers of atmosphere is distributed almost homogeneously over a large area around the shower core.

The numerical calculations of the Cherenkov light in EAS carried out by Zatsepin & Chudakov (1962) gave the first systematic and quite precise theoretical predictions on the different characteristics of the Cherenkov light generated in air showers. However they were renewed later by the Monte Carlo simulations.

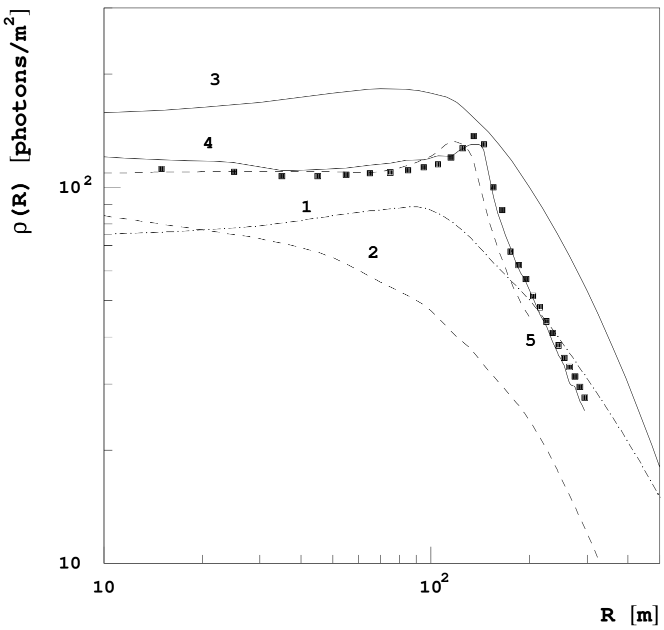

Fig. 3: Lateral distribution function of Cherenkov photon density, $\rho(r)$, in 1 TeV γ-ray-induced air shower at sea level (wavelength range is of $\Delta\lambda = (0.3 \div 0.6)\ \mu m$) calculated by Zatsepin & Chudakov (1962) (curve 1), Castagnoli et al. (1967) (curve 2); Ivanenko et al. (1980) (curve 3); Hillas (1996) (curve 4); Sinha (1995) (curve 5). Black dots correspond to the present calculations.

Note that calculating the lateral distribution of the Cherenkov light photons emitted in air shower is a very complicated task for an analytical or semi-analytical methods (e.g. Ivanenko et al., 1980). More effective seems to be the Monte Carlo approach which properly reproduces not only the average energy dependent space and angular cascading of the shower particles but also the shower fluctuations. We should mention amongst the Monte Carlo simulations undertaken in the relatively far past the works of Castagnoli et al. (1967); Rieke (1969); Browning & Turver (1977); Acharya et al. (1982); McComb & Turver (1982); Patterson & Hillas (1983); Rao & Sinha (1988). The comparison of these results reveals some contradictions in the shape of the lateral distribution of the Cherenkov light as well as in the absolute Cherenkov light flux at sea level which is mainly connected with certain assumptions used to simplify the computing technique. However these numerous efforts defined more precisely the parameters of Cherenkov light emission in air showers. In particular, a two component model of *direct* and *diffuse* Cherenkov light emission was proved and studied by Rao & Sinha (1988) in detail by introducing the artificial energy threshold of cascade electrons at 1 GeV in the electromagnetic shower of energy 100 GeV. It was shown that high energy electrons ($E_e > 1$ GeV) are responsible for the hump in the lateral distribution of the Cherenkov light. Many questions on the physics of the cascade development in respect to the Cherenkov light emission from EAS have been asked by Hillas & Patterson (1990). Recently results of Monte Carlo simulations have been published by Konopelko et al., (1992), Sinha (1995), Hillas (1996). The data shown in Figure 3 illustrates how different the predictions on the lateral distributions of the Cherenkov light were in the past (curves 1,2,3) and how close the recent Monte Carlo simulations are now (curve 4,5,6).

The lateral distribution functions of the Cherenkov light density calculated for a γ-ray-induced air shower of 10 GeV at different observation levels are shown in Figure 4(a). The Cherenkov light density in the range of the impact radius $0-140$ m essentially increases with the height of the observation level because of less influence of the atmospheric absorption. The Cherenkov light densities at 2.2 km and 3.5 km above the sea are respectively in 1.5 and 2 times higher compared with the density at sea level. At high altitudes it is possible to collect more Cherenkov photons from the shower and consequently to reduce the energy threshold of the detector while all other parameters are fixed. Observing at higher altitudes above the sea

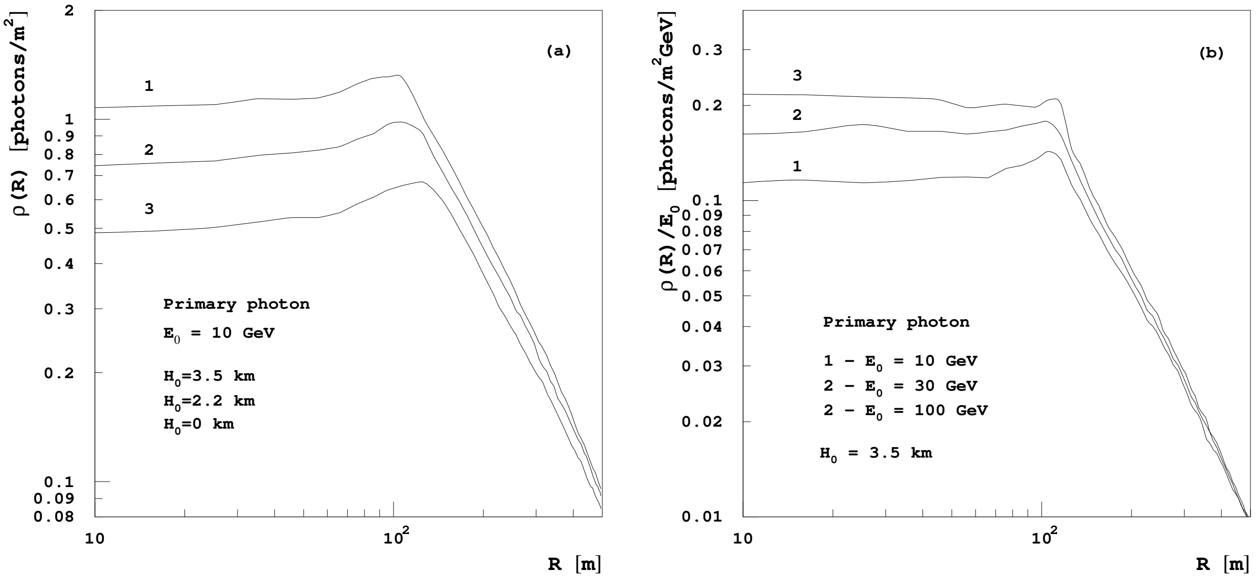

Fig. 4: Lateral distribution function of Cherenkov photon density, $\rho(r)$, in 10 GeV γ-ray-induced air shower calculated at different heights above sea level (a). Normalized density of Cherenkov light photons, $\rho(r)/E_0$, in air electromagnetic shower of a primary energy 10, 30, 100 GeV calculated at H_0= 3.5 km above the sea.

the shower becomes closer to the detector and the impact radius corresponding to the hump slightly decreases (see Figure 4(a)) also the hump itself becomes less prominent. The diffuse emission noted above smears out the so-called direct emission at high altitudes. The same effect could be seen for a fixed observation level but increasing the primary shower energy (see Figure 4(b)).

4. Fluctuations in the Cherenkov light amplitude

An important issue which arises when detecting Cherenkov light from air showers is the fluctuations in a number of registered photons in individual events. These fluctuations affect temporal and angular distributions of the observed light flashes. Naively one can assume that the fluctuations in photon amplitude have a pure Poisson nature. In fact the Monte Carlo simulations Konopelko et al., (1991a), Sinha (1995) revealed much larger fluctuations than one can expect from Poissonian statistics.

The results of Monte Carlo simulations for γ-ray-induced air showers of energy 10, 50, 100 GeV at 2.2 km above the sea are shown in Figure 5. The amplitude fluctuations depend on primary energy, impact distance from the shower as well as on the area of the optical reflector. The following expression is relevant

$$\delta^2(N) = D(N)/N^2 >> 1/N. \tag{9}$$

In reality optical detectors collect the Cherenkov light photons coming form the air shower not independently but by a certain number of Cherenkov light "clusters". The photons of a cluster come from the same emitting cascade electron and are highly correlated in time and angular space. Thus the observed photon amplitude is a sum over a number of clusters each with a different photon content

$$N = p_1 + p_2 + p_3 + ... + p_n \simeq < p > n \tag{10}$$

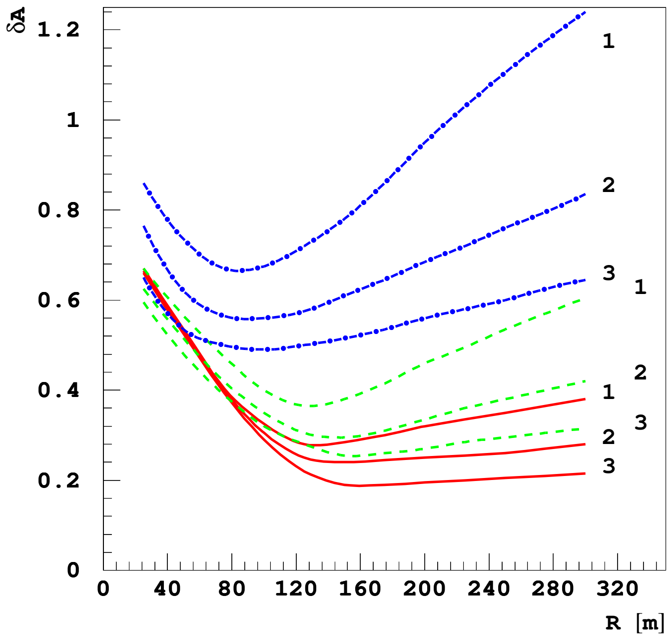

Fig. 5: Fluctuations in a number of detected Cherenkov photons (amplitude), $\delta A = \sigma A/A$, detected by the optical detector with the mirror size of 250 m^2 (solid); 50 m^2 (dashed); 10 m^2 (dotted-dashed), from a γ-ray-induced air shower of energy 10 (curve 1); 50 (curve 2); 100 (curve 3) GeV.

It could be simplified by the model of independent registration of n clusters with the averaged number of photons $< p >$ which could explain the high level of the fluctuations

$$\delta(N) = < p > /N = 1/n \qquad (11)$$

and also dependence of the fluctuations on energy, impact distance and area of the optical reflector $\delta^2(E, R, S)$. It means that fluctuations of photon amplitude depend in general on the number of detected clusters. The high energy electrons in the cascade maximum contribute in the impact energy range $\simeq 125$ m that provides a large number of independent clusters whereas at small impact distances from the shower core photons come mainly from a few electrons at the cascade "tail".

In addition note that other source of fluctuations in the measured photon amplitudes is associated with the propagation from initial photons to the output photoelectrons (which is out of present discussion). Finally we may conclude that only direct Monte Carlo simulations of air shower development accompanied by the simulations of the detector response could serve as a tool for the performance studies of the Cherenkov technique.

5. Time structure of the Cherenkov light pulses

The time pulse of the Cherenkov light measured at a certain distance from the shower core strongly correlates with the longitudinal development of a shower. The simultaneous registration of Cherenkov light time pulses by a number of detectors scattered over a large area at the observation level is usually used for accurate reconstruction of the arrival direction of multi-TeV air showers (e.g. AIROBICC, Themistocle). At the same time the structure of the measured Cherenkov light pulses could be used for the separation of γ-ray-induced air showers from cosmic ray air showers. For the first time Tümer et al., (1990) applied this technique experimentally by sorting out the pulses with irregular shape ("multi-hump" events). The Monte Carlo studies of Konopelko et al., (1991b) have shown that fluctuations of the pulse shape are much lower for γ-ray-induced showers compared with cosmic ray showers. This difference ultimately could be used effectively for the shower classification. Recently the data acquisition systems based on the Flash ADC readout (see for detail Hess et al., 1997) make it possible to measure simultaneously the Cherenkov light pulses in each channel of a multi-channel imaging camera installed at the telescopes designed to observe γ-rays of 500 GeV (see Daum et al., 1997). This technique makes straightforward testing the efficacy of cosmic ray rejection based on timing information.

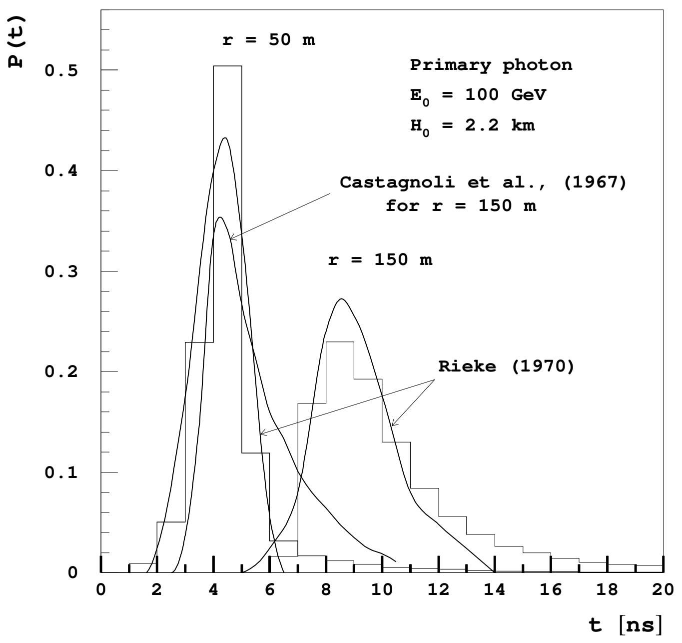

Fig. 6: Time pulses of Cherenkov light photons in γ-ray-induced air shower of 100 GeV predicted by Monte Carlo simulations. Histograms correspond to the present simulations.

For the forthcoming low energy Cherenkov detectors the timing technique could also be used. In this concern it is interesting to look for the time pulses from 10 GeV air showers at different impact distances from the shower core in observation plane.

The exact treatment of the time structure of the Cherenkov light in air showers using analytical methods usually fails because it needs to take into account the curvature and thickness of shower particle front as well as the Cherenkov light emission angle in respect to the track of the charged particles. The latter is actually the subject of independent studies (see for detail Ivanenko et al. (1980)). The Monte Carlo simulations could serve for that.

The first Monte Carlo calculations by Castagnoli et al. (1967) and Rieke (1969) demonstrated significant differences both in the predicted absolute time delays and in the time pulse shape (see Figure 6). For comparison simulations under mostly the same conditions have been carried out using the Altai Monte Carlo Code (see Figure 6,7). From the results shown in Figure 6 one may find a good agreement with the calculations of Rieke (1969). Probably it is a result of a certain coarse approximations used in Castagnoli et al. (1967) e.g. regarding the simulations of the Cherenkov light cone.

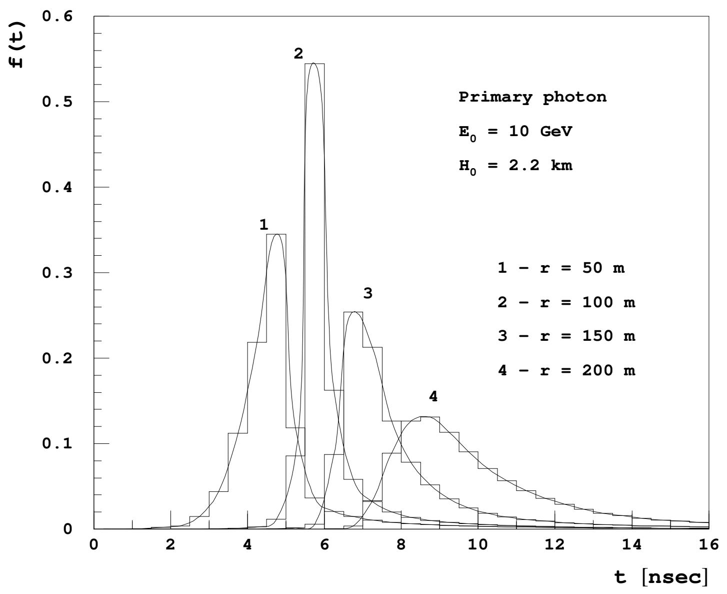

Fig. 7: Average Cherenkov light time pulses calculated at different distances from shower core in an air shower induced by γ-ray of 10 GeV. The observation level is at 2.2 km above the sea.

Note that Cherenkov time profiles in proton-induced air showers of primary enegies of $10^{15}, 10^{16}, 10^{17}$ eV were calculated by Patterson & Hillas (1983) from Monte Carlo simulations.

For better understanding the Cherenkov light time structure from air shower the analytical estimate of the curvature of the Cherenkov light front at the observation level could be made in the following way. First let us ignore the lateral development of the cascade. It means that all electrons move along the shower axis. The time delay of the Cherenkov photons emitted at some point at the shower axis in respect to the electrons moving in a shower core is calculated as

$$t(R) = \int \frac{dl}{v(l)} - \frac{H}{c} \qquad (12)$$

where R is the impact distance from the detector to the shower core, H is the height above the observation level where Cherenkov photons come from, and $v(l)$ is the speed of light on the way to

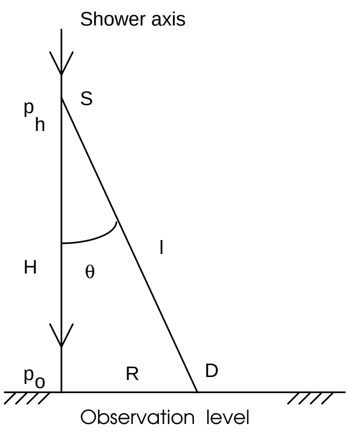

Fig. 8:

the detector (see Figure 8). The function $v(l)$ could be approximated by

$$v(l) = v(h) = c/n = c/(1 + (\eta_0/\rho_0) \cdot \rho(h)), \qquad (13)$$

where $\rho_o = 1.29 \cdot 10^{-3}\mathrm{gr/cm}^2$ is the atmospheric density at sea level. After the simple transformations Eqn. (11) could be written as

$$t(R) = \frac{H}{c}(\frac{1}{cos\theta} - 1) + (\eta_0/\rho_0)\frac{(p_o - p_h)}{c \cdot cos\theta} \qquad (14)$$

where the first term reproduces the pure geometrical time delay whereas the second term determines the difference of light speed in atmosphere. For a γ-ray-induced air shower of the fixed primary energy the time delay at the observation level is simply constant in a range $R \ll H$ and a linear function in the range $R \gg H$ e.g.

$$t(r) \propto (H^2 + R^2)^{1/2} \qquad (15)$$

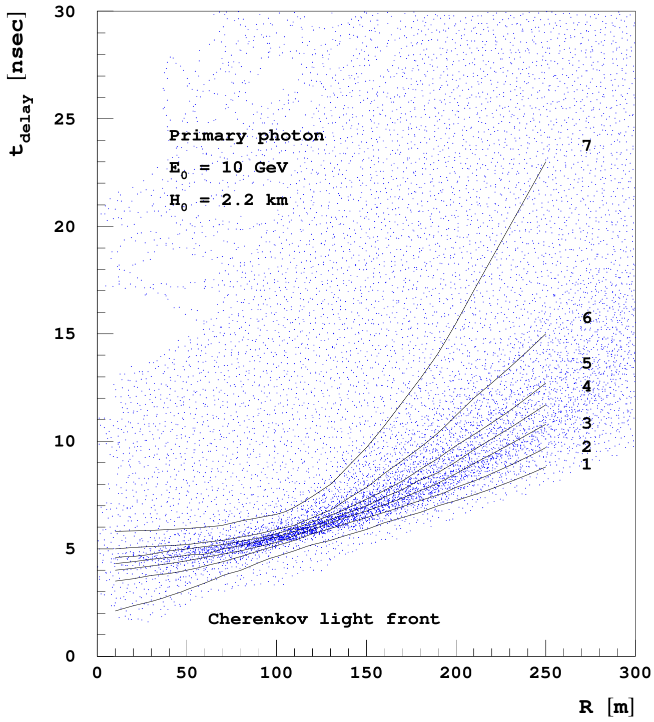

Fig. 9: Time structure of Cherenkov light pool in a γ-ray-induced air shower of 10 GeV at the observation level of 2.2 *km above sea level. Time delays are calculated at 10% of pulse maximum (curve 1), 50 % (curve 2), 90% (curve 3) for a pulse rise, in pulse maximum (curve 4) and also for a pulse fall at 90% (curve 5), 50% (curve 6), 10% (curve 7) of pulse maximum.*

As follows from Eqn. (13) the Cherenkov light emitted by the cascade electrons deeply penetrating in the atmosphere will be detected earlier than the photons coming from the upper layers of the atmosphere in the detector placed not far from the shower core $R \leq 150$ m. The situation changes to the opposite when the detector is placed at larger impact distances.

The time pulses shown in Figure 7 demonstrate the time distributions for the region of the small impacts, transition region and region of large distances from the shower core. The time pulse in the transition region $\simeq 120$ m is very narrow in comparison with others.

For the 10 GeV γ-ray-induced air shower at 2.2 km above the sea the time delays at the maximum of the pulse (which approximately corresponds to the photons coming from the shower maximum H = 13 km, $p_h \simeq 165$ gr/cm^2) could be estimated by the following equation

$$t(R) \simeq a(b + R^2)^{1/2} - c, \qquad (16)$$

where $a = 3.33378, b = 1.1664 \cdot 10^8, c = 3.6 \cdot 10^4$. In Figure 9 the photon delays

Table 1: *Curvature of Cherenkov light front, $r = c \cdot \tau(R)$ [m], in γ-ray-induced air shower. $\tau(R)$ is a delay in pulse maximum.*

E_0, GeV	R [m] = 12	37	62	87	112	137	162	187	212	237	262
10	1.6	1.7	1.9	2.0	2.2	2.3	2.5	2.9	3.1	3.4	3.9
10^2	1.5	1.7	1.6	1.9	2.2	2.2	2.5	2.8	3.4	3.6	4.3
10^3	1.3	1.3	1.6	1.9	1.9	2.0	2.5	3.1	3.4	4.0	4.6

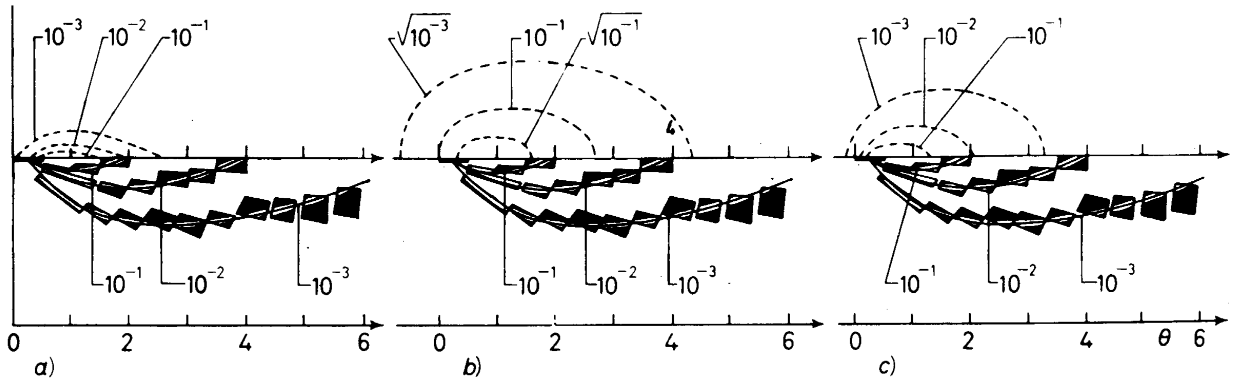

Fig. 10: Comparison plot of isophote contours of Cherenkov light density at 100 m distance from a γ-ray-induced air shower calculated by Castagnoli et al. (1967) (low panel) with the results of ((a) Zatsepin (1965), $\mathrm{E}_0 = 10^{12}$ *eV, at sea level; (b) Long (1966),* $\mathrm{E}_0 = 10^{11}$ *eV, at 2 km above sea; (c) Rieke (1969),* $\mathrm{E}_0 = 10^{11}$ *eV, at 2.3 km above the sea. Picture is taken from Porter & Weekes (1978).*

versus the impact distance in 10 GeV γ-ray air shower are shown. The structure of the front repeats basically the simple mind analytical estimates made above.

In Table 1 data on the Cherenkov light front in showers of different primary energy and different impact distances are shown. The logarithmic elongation of the shower development with primary energy does not strongly change the curvature of the Cherenkov light front. Note that the general behavior could be well approximated by the function presented by Eqn. (14).

6. Cherenkov light image from air shower

For the first time Hill & Porter (1961) made a photograph of the Cherenkov light flash from an air shower. Since then a lot of experimental and theoretical studies have been done for understanding the two-dimensional angular distribution (image) of the Cherenkov light from air showers. The special interest in that is associated with a dramatic development of a very high energy (VHE) γ-ray astronomy based on the detection of the Cherenkov light images with the optical reflectors having multi-channel camera installed in the focus (e.g. Weekes, 1996).

The attempt to calculate analytically the angular distributions of the Cherenkov light emitted from the air showers initiated by the primary γ-ray and proton has been undertaken in the pioneer works of Zatsepin (1964), Long et al. (1966). Monte Carlo studies have appeared somewhat later by Rieke (1969), Castagnoli et al. (1972), and Browning & Turver (1977).

These earlier calculations have been carried out for various observation levels, primary shower energies (100 GeV and above), impact distances from the shower core, however, they provided important conclusions. In particular it was shown that increasing the impact distance from the shower core, r, leads to increase of the angular distance between the arrival direction of the shower (it coincides with the center of focal plane if the optical reflector is directed along the shower axis) and the maximum of light intensity in image (centroid position), Θ_m. Thus for a 1 TeV γ-ray-induced air shower the variation of impact distance from 0 to 100 m reflects in a change of Θ_m roughly linearly from 0 to $\simeq$1 degree. However the attempt to compare the isophote contour lines of equal density for the early Monte Carlo simulations demonstrates essential differences (see Figure 10). Test simulations have been done using the Altai Monte Carlo code for γ-ray-induced air showers of energy 100 GeV and observation level 2.2 km above the sea. The results of the simulations shown in Figure 11 are in a good agreement with the simulations of Rieke (1969). The difference in isophote contours compared with other simulations could be connected with simplifications of the space-angular development of the cascade electrons which strongly influence the Cherenkov light angular image.

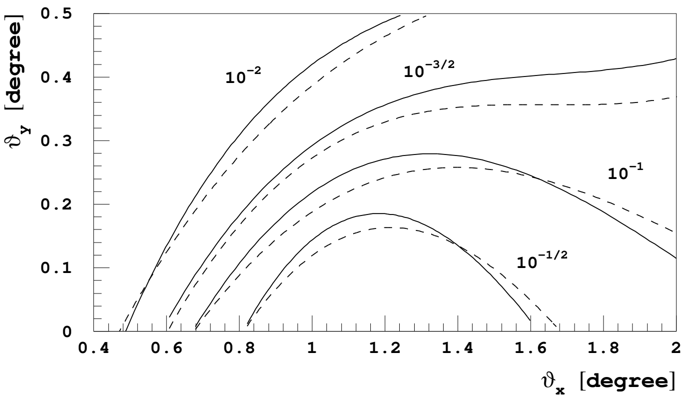

Fig. 11: Isophote contours of two-dimensional Cherenkov light angular distribution in a γ-ray-induced air shower of 100 GeV (H_0 = 2.2 km; the distance to the shower core is of 200 m. Solid curves correspond to the present data, dashed curves correspond to calculations by Rieke (1969).

The idea to separate the γ-ray-induced and cosmic ray -induced air showers on the basis of the two-dimension angular image of the Cherenkov light has been expressed already by Hill & Porter (1961). However the calculations by Zatsepin (1964) had demonstrated a similar shape of the Cherenkov light images from primary γ-rays and protons. The results of Browning & Turver (1977) showed a high level of fluctuations in the image shape. All that sowed a pessimism in respect to the possibility of classifying the images from γ-ray-induced and cosmic ray air showers. Nevertheless in the paper of Weekes & Turver (1977) the method of image registering was suggested which was for the first time embodied by Whipple group (e.g. Cawley & Weekes, 1995). The analysis method of the event separation was developed by Hillas (1985).

Presently the Cherenkov light image is measured by the multi-channel camera installed in the focus of the optical reflector. The detected image is actually the matrix of the PMTs (channels) responses for each event. According to the procedure of Hillas (1985) the shape of the image is characterized by the basic parameters: *Distance*, the distance of the image centroid from center of field of view; *Width, Length*, the lateral and longitudinal image size, and *Alpha*, the angle between the major axis of the image and the line connecting the point of the maximum image intensity and center of the field of view. These parameters provide a strong suppression (at least in 100 times) of the cosmic ray background events saving half of the γ-rays. The parameters of the cosmic ray images (very soon the images of γ-rays also) measured in experiment could be directly compared with the Monte Carlo simulations (see Figure 12).

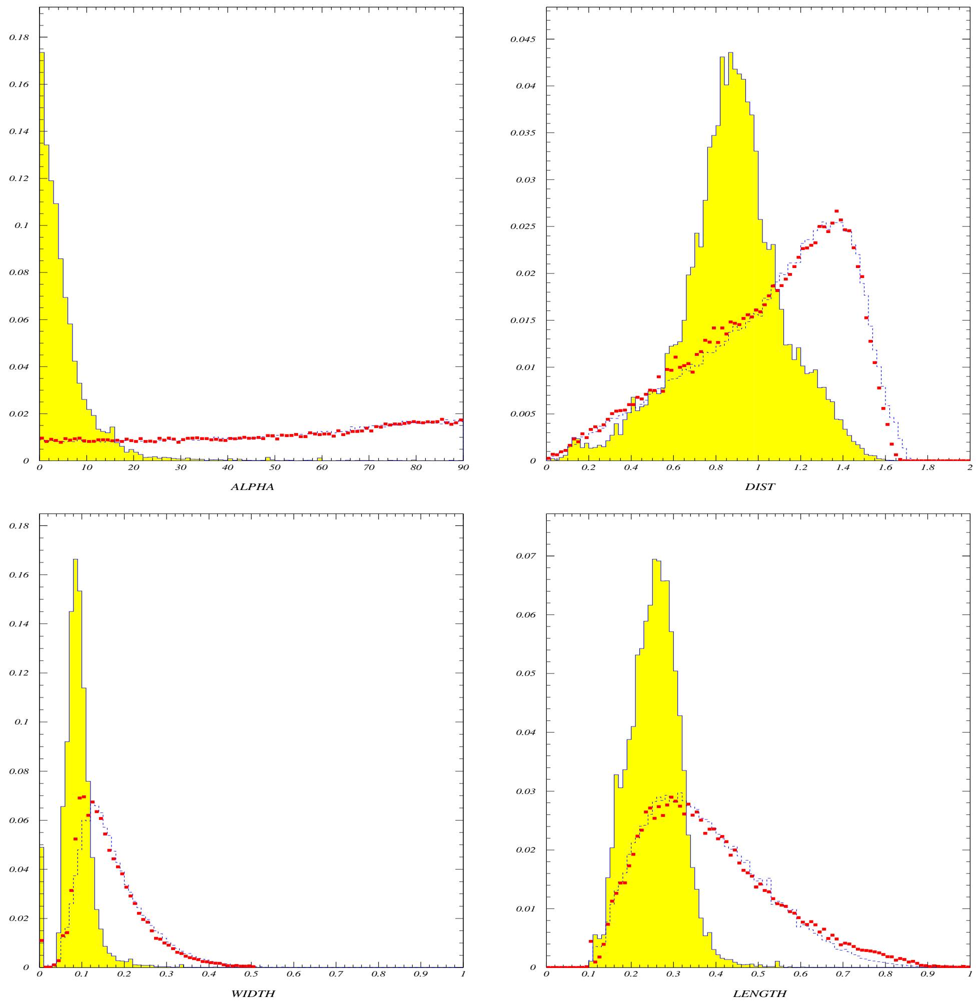

Fig. 12: Distributions of Cherenkov light image parameters. Dots correspond to Monte Carlo simulated CR events, dashed histograms show the data (HEGRA CT-3 stand alone). Hatched histograms correspond to Monte Carlo γ-ray-induced air showers. Courtesy of M. Hemberger (HEGRA collaboration).

A significant improvement of the imaging technique comes from stereoscopic observations with more than 2 telescopes operating in coincidence mode. The stereoscopic observations make it possible to reconstruct the arrival direction of individual air showers as well as to measure the distance from the telescope to the shower core in the observation plane using the layout and orientation of a several images detected for a certain event. It dramatically improves the angular and energy resolution of the technique and consequently increases the detection sensitivity for observing γ-ray source candidates (see for detail Aharonian et al., 1997). The concept of stereoscopic observation forms the basis for the currently operating HEGRA system and for the forthcoming IACT arrays HESS and VERITAS planned to achieve the energy threshold of 50-100 GeV.

The important question is how far one can decrease the energy threshold of imaging technique still retaining the advantages and main features of this approach ? It seems to be important regarding the very low energy ($\simeq 10$ GeV) imaging future instruments like MAGIC single dish imaging Cherenkov telescope.

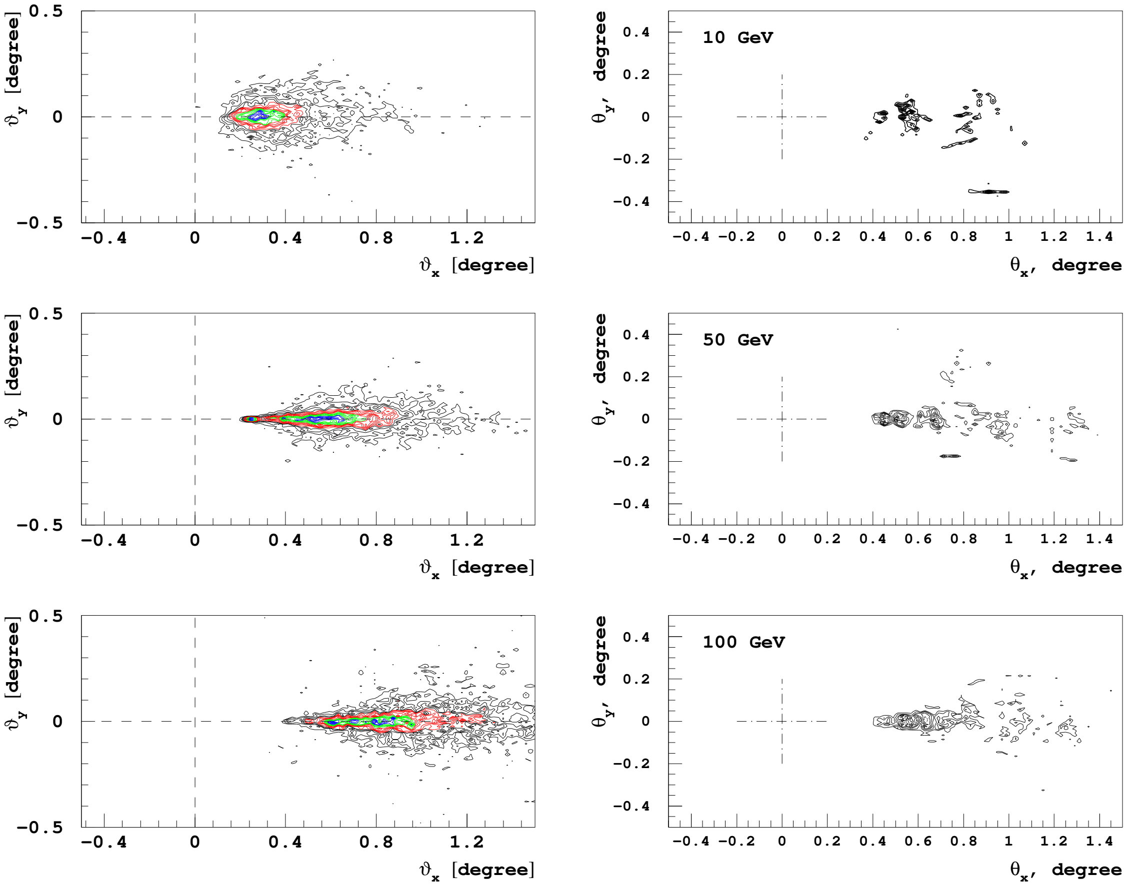

Fig. 13: Images from 10 GeV γ-ray-induced air shower at distance 50, 100, 150 m from the shower core and 2.2 km above sea (left panel). Images from individual air shower of 10, 50, 100 GeV observed by 250 m^2 *telescope (infinite resolution) at 100 m from a shower core (right panel).*

The Monte Carlo predicted Cherenkov light images (averaged over a large event sample) from 10 GeV γ-ray-induced air showers are shown in Figure 13, left panel). They demonstrate the common features of the images for the 100 GeV - 1 TeV energy domain. The images are elongated with ellipsoidal shape and well defined orientation. Taking the telescope with the reflector area of a reasonable size 250 m^2 one can look on the expected Cherenkov light images from the 10, 10^2, 10^3 GeV in the individual air shower (see Figure 13, right panel). Compared with others the 10 GeV image certainly contains fewer photons and has a coarse shape. An image orientation is almost lost. Stereoscopic observation seems to be most promising approach for the very low energy domain down to $\propto$ 10 GeV. The simultaneous detection of several images might provide still a fairly good angular resolution and rejection power. The detailed results of Monte Carlo simulations for 20 GeV IACT array will be published elsewhere. It should be also mentioned that for the energy threshold getting down to 10 GeV the content of the cosmic ray electrons detected by IACT becomes an important issue. The images from the air showers produced by primary CR electrons have the same shape as images from γ-ray-induced air showers and could be sorted out by orientation. Thus observations of air showers by a number of telescopes in the stereoscopic mode may be very important means to get sufficient angular resolution and suppress the isotropic electron flux.

7. Spectra of Cherenkov photons at the observation level

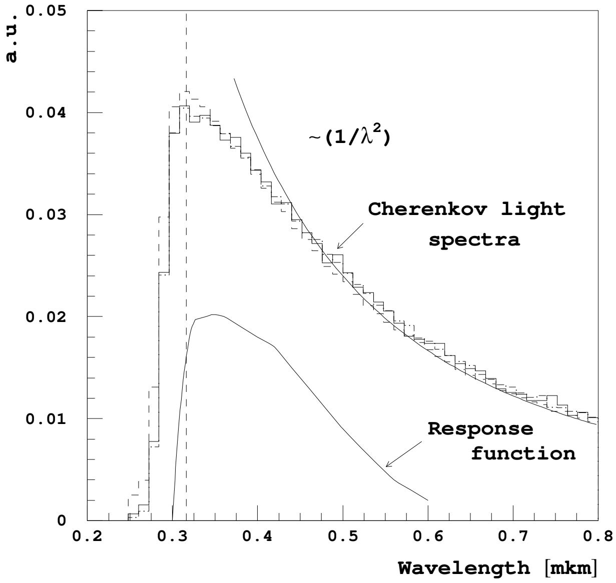

Fig. 14: A Cherenkov light spectrum from γ-ray-induced air shower of 10 (solid), 50 (dotted-dashed), 100 (dashed) GeV at 100 m from the shower core and 2.2 km above the sea.

The spectrum of the Cherenkov photons at the observation level is formed by the original emission spectrum $\propto \lambda^2$ of the Cherenkov light photons and the atmospheric absorption being strongly wavelength dependent. Usually the Cherenkov photons are observed in the 0.3 - 0.6 μm wavelength range excepting the specific experiments used to observe the Cherenkov light in UV region. The Monte Carlo simulations show that the spectrum of the Cherenkov light photons does not depend significantly on the primary energy of the shower or on the observation level (0-3.5 km above sea) in a range 0.3 - 0.6 μm and very little on distance from shower axis. The normal Cherenkov light spectrum is shown in Figure 14. Note that an important issue in registration of the Cherenkov light is to gain in detector response in the wavelength range 0.3-0.35 μm where the spectrum goes up rapidly.

8. Conclusions

The present paper gives an overview of lateral, temporal and angular characteristics of γ-ray-induced air showers of energy 10-100 GeV. The results of Monte Carlo simulations presented here could be used for performance studies of low energy ($\ll$ 100 GeV) Cherenkov light detectors. Certainly this first step in understanding the phenomena of Cherenkov light emission in low energy air showers would be accompanied by further detailed considerations related to the particular experimental technique.

9. Acknowledgements

I would like to thank F. Aharonian, W. Hofmann and H.J. Völk for the hospitality at Max-Planck-Institut für Kernphysik, Heidelberg, and numerous useful discussions. I thank O.C. de Jager for the kind invitation to give this talk, A.M. Hillas for very helpful discussions of the paper and remarks on the manuscript.

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