All Sky Monitor for Energetic γ-rays

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Abstract. Survey over all the sky by energetic γ-rays would uncover new, mysterious aspects of the Universe that are otherwise hard to see; violently time variable, hidden sources, extended emission, and exotic mechanism for high energy radiations. Imaging air Čerenkov telescope of a large solid angle is available by using Fresnel lens refractor. Such telescope accepts air scintillation lights with detection area ≥ 100 km^2, and provides deeper survey at higher energies, pushing forward the high energy frontier of γ-ray astronomy.

INTRODUCTION

Evidence of TeV γ-rays has been so far only from the objects that are already known in other wavelengths. The field of view of $\sim 10^{-2}$ steradian is not sufficiently wide to allow a quick scan over all the sky. Detection has not been successful yet, but giving upper limits [1], from the Galactic disc that is the brightest emission in the GeV γ-ray sky. As an all sky monitor of GeV γ-rays, the GLAST is coming soon and may serve as a guide to VHE γ-ray observation. However, the GeV and TeV sources have shown features dissimilar to each other as evidenced in pulsars, blazars and SNR (supernova remnants), encouraging the efforts for unknown objects that are intense in TeV but not in the GeV band.

By using the Fresnel lens, which is being developed for OWL project [2] [3], instead of the reflector mirrors, the field of view can be extended to as large as 60°. All sky monitor for TeV γ-rays is thus feasible and will be even of easier practical use than the conventional reflector telescope [4].

Very high energy (VHE) γ-ray astronomy at TeV energies owes its success to the detection area as large as ~ 0.1 km^2 and the angular resolution of $\sim 0.1°$ of IACT (imaging air Čerenkov telescope), providing sufficient statistics and a high power of rejecting cosmic ray backgrounds. Similarly, all sky monitor needs to have angular resolution as good as $\sim 0.1°$ throughout the wide field of view.

LARGER DETECTION AREA AND DEEPER SURVEY

The sensitivity of IACT for VHE γ-rays is about 10^{-12} erg cm^{-2} s^{-1} or 10^{-12} cm^{-2} s^{-1} in terms of the number of γ-ray photons of > 1 TeV. The intensity of the Crab nebula, the "standard" TeV source, is about 10^{-11} cm^{-2} s^{-1} for > 1 TeV, the detectable intensity ranging not much wider than one order of magnitude. On the other hand, in X-ray band, for instance, the intensity of the source observed covers several decades from $\sim 10^{-14}$ erg cm^{-2} s^{-1} of distant AGN (active galactic nuclei) to 10^{-9} erg cm^{-2} s^{-1} from the Crab nebula/pulsar. The sensitivity is limited by statistics in VHE γ-ray astronomy. Detection area of single IACT, about $0.1 km^2$, collects about 100 photons of 1 TeV energy during 24 hrs observation for the flux of 10^{-12} cm^{-2} s^{-1}. Thus, deeper survey requires detection area larger than ~ 0.1 km^2 of the air Čerenkov light pool.

Isotropic emission of air scintillation lights presents a huge detection area, however, at the cost of higher threshold energy. The total number of photons is of similar amount between Čerenkov and scintillation lights from a given air shower. However, Čerenkov photons are concentrated into $\sim 10^{-2}$ sr along the direction of incoming γ-rays, while scintillation lights are isotropic into $4\pi \approx 10$ sr. Accordingly, the number of scintillation photons received by telescope is roughly $(10^{-3} \sim 10^{-4})$ of Čerenkov lights, and the threshold energy of detectable γ-rays is about $3 \sim 4$ orders of magnitude higher for scintillation lights.

In order to detect ~ 1 TeV γ-rays through scintillation lights, it is necessary to use a light collector of ~ 100m size (unless quantum efficiency is dramatically improved), which are not easy to construct. However, observation near 1 PeV, which is realistic with the current telescope size, is no less interesting, and it is worthwhile to begin with this energy region. The detection area S necessary for γ-rays of energy higher than E can be estimated to be $\mathrm{S} \geq 0.1\mathrm{km}^2(\mathrm{E}/1\,\mathrm{TeV})$, by extrapolating the differential γ-ray flux proportional to E^{-2}, from the area ~ 0.1 km^2 of IACT. The condition is satisfied in the PeV γ-ray observation through scintillation lights from the distance of ~ 10 km.

TELESCOPE OF A LARGE FIELD OF VIEW

Angular resolution and γ-ray signal

We observe the image of Čerenkov and scintillation light as illustrated in Figure 1. The location of the image in the field of view is displaced from the true direction by δ and β, respectively, along and perpendicular to the major axis of the elliptic image. The δ distributes from 0° up to $\sim 1^\circ$ for Čerenkov lights. The elongated image of γ-ray shower points toward the true direction with error angle α which is less than about $10^\circ \approx 0.2$ radian in most of the contemporary IACTs, and thus the deviation β is equal to $\alpha\delta \approx 0.1^\circ$. Stereoscopic observation by multiple telescopes can determine both of β and δ. On the other hand, it has been also attempted to estimate δ from the elliptic and asymmetric shape of the image and from the arrival time structure. In the case of scintillation lights, the distance δ can be larger than 10°, so that the transverse error β becomes as large as $\delta\alpha \sim 1^\circ$. However, the path length of scintillation lights varies to large extent with δ, enabling a longitudinal accuracy of $\sim 0.1^\circ$ in δ from analysis of the acquisition time of the lights.

The large field of view receives many events at high rate. It is a "time-wasting" task to analyze all the events to search for evidence of emission by scanning the large field of view with 0.1° angular resolution. Thus, the merit of all sky monitor capable of watching a wide area of the sky can not be utilized to a full extent, unless we monitor possible γ-ray signals to predict likely directions of the emission and to guide the analysis of 0.1° resolution. In Table 1, expected counting rates at 1 TeV are listed for the background of cosmic rays, γ-rays from the Galactic disc (see for an example [5]), GRB (γ- ray burst), which is assumed at ~ 1 TeV to have fluence of $10^{-9} \sim 10^{-7}$ erg cm^{-2} s^{-1} as large as that observed at ~ 100 keV energies [6], and a source of 10^{-11} erg cm^{-2} s^{-1}. The solid angle of 10^{-3} sr (angular size of 1° radius) is assumed for prompt procedure of regarding the centroid of image as the true direction. The second column of 0.1 sr and 3hrs corresponds to the case when events are collected during one night from the whole Galactic disc within the field of view. Table 1 suggests that the signal from GRB can appear above the statistical fluctuation of cosmic rays. The monitor by the rough scan of $\sim 1^\circ$ size would be able to indicate the signal if the emission continues as intense as the Crab for more than 10 days. The excess counts from the Galactic disc can be marginally

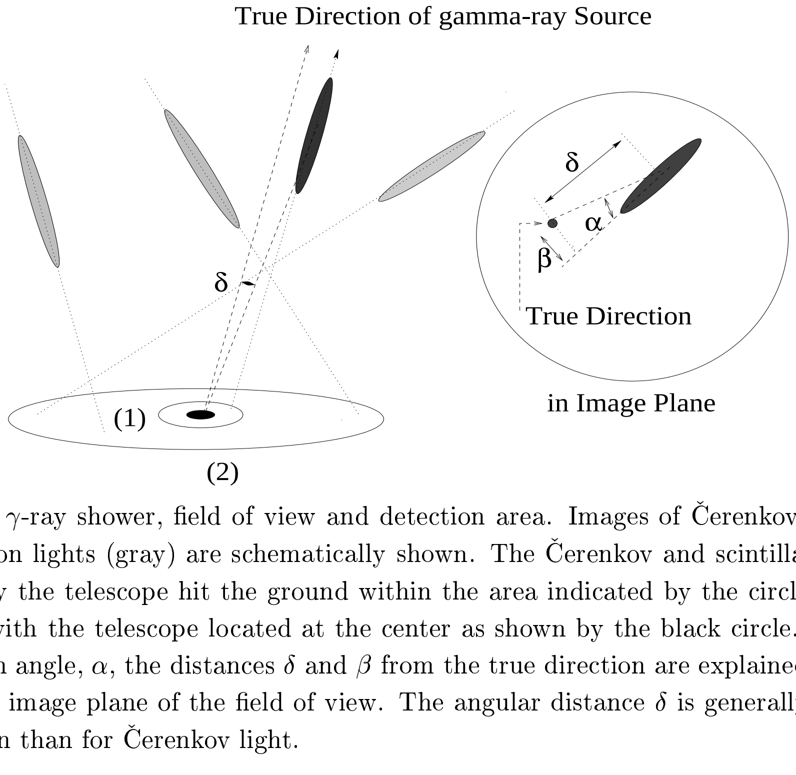

FIGURE 1. γ-ray shower, field of view and detection area. Images of Čerenkov (black color) and scintillation lights (gray) are schematically shown. The Čerenkov and scintillation lights to be detected by the telescope hit the ground within the area indicated by the circle (1) and (2), respectively, with the telescope located at the center as shown by the black circle. In the right, the orientation angle, α, the distances δ and β from the true direction are explained (see text for details) in the image plane of the field of view. The angular distance δ is generally much larger for scintillation than for Čerenkov light.

TABLE 1. Event rates of cosmic ray background and γ-ray signal.

solid angle (sr)	duration time (s)	cosmic rays	emission from Galactic disc	GRB	a source of 10^{-11} erg cm^{-2} s^{-1}
10^{-3}	1	~ 10	$\sim 10^{-3}$	$1 \sim 100$	0.01
10^{-1}	10^{4}	$\sim 10^{7}$	$\sim 10^{3}$	—	—

detected from ~ 10 nights' observation (possibly from one night if the difference in image shape and the triggering efficiency are taken into accounts between čosmic ray and γ-ray events). Such a signal from the Galactic disc would be also useful to monitor the telescope system, to calibrate the response of camera over the total field of view, and to correct for systematic errors.

Scintillation lights

The arrival time of scintillation lights is determined by the geometry of the path length of the lights (Figure 2). Let us define the time $T = 0$ by the arrival time at telescope of such imaginary photons that are emitted at the infinitely high altitude (*i.e.* incident from $\delta = 0°$), where δ is the angle which the direction of light-emitting point makes against γ-ray direction (*i.e.* $\delta = 0°$ is the direction of the γ-ray source), and ρ is the distance to the trajectory of γ-ray. The time T when the light arrives from the direction δ is $\rho \cdot (1 - (cos\,\delta/n))/sin\delta$, where n is the refractive index of the atmosphere. The difference of n from 1 is not negligible only when $cos\,\delta \approx 1$ (*i.e.* $\delta \approx 0$ or in the case of Čerenkov radiation) and numerical calculation such as Monte Carlo simulation is necessary for understanding this case. We consider the case of scintillation lights ($\delta \gg 1°$) in the followings, and set $n = 1$.

Relative arrival time and its derivative are, respectively, calculated as

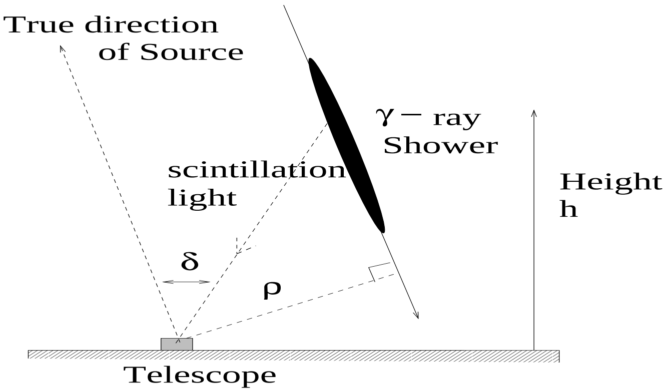

FIGURE 2. Path length of scintillation lights.

$$\frac{dT}{d\delta} = \rho \cdot \frac{1 - cos\,\delta}{sin^2\delta} \quad \text{and} \quad \frac{d^2T}{d\delta^2} = \rho \cdot \frac{(1 - cos\delta)^2}{sin^3\delta} \ . \tag{1}$$

When δ is measured in a step of $\Delta\delta$ (corresponding to the pixel size of the camera of the telescope), two observables, A (the changing rate of arrival time per $\Delta\delta$) and B (the derivative of A) are $A = \Delta\delta(dT/d\delta) = \rho\Delta\delta(1 - cos\,\delta)/sin^2\delta$ and $B = \Delta\delta(d^2T/d\delta^2) = \rho\Delta\delta(1 - cos\,\delta)^2/sin^3\delta$. From these two relations, we can solve δ and ρ. The true direction δ and the distance ρ are thus calculated from observational data, as

$$sin\,\delta = \frac{(2B/A)}{1 + (B^2/A^2)} \quad \text{and} \quad \rho = \frac{(2B)}{1 + (B^2/A^2)} \cdot \frac{1}{\Delta\delta} \ . \tag{2}$$

The magnitude of A and B is proportional to the distance ρ, and when $\rho \approx$10 km, A and B are in the order of 10μs. The error in calculating δ is estimated to be

$$\approx \frac{B}{A} \cdot (|\frac{\Delta A}{A}| + |\frac{\Delta B}{B}|) \cdot \frac{1}{cos\,\delta} \ . \tag{3}$$

By measuring the arrival time in the accuracy of $\sim$ 10 ns, δ can be determined with an error $\sim$ 10 ns/10 μs = 10^{-3} radian $\sim 0.1°$. However, the expression (2) is to be applied to each pixel, and δ is different for different pixel. The degree of variation over the pixels is given by $(\Delta l/\rho)\,sin\langle\delta\rangle$, where $\langle\delta\rangle$ is the average value over the pixels and Δl is the length of the γ-ray shower. The average value $\langle\delta\rangle$ corresponds effectively to the δ at the center of the image. The error may be better estimated of $\langle\delta\rangle$, rather than for each δ of each pixel. The error also depends on experimental conditions, such as the trigger scheme and the procedure of data acquisition, consideration on these technical details being not in the scope of the present paper. The accuracy of determining δ in the real case, however, will not be very different from $\sim 0.1°$ as estimated above.

The error given by the expression (3) increases when δ approaches 90°. In order to keep the error as small as 0.1°, the distance ρ should be not much larger than the scale height, h $\sim$10 km, of the atmosphere or the height where γ-ray shower has the maximum number of shower particles which emit scintillation lights. Let us consider such γ-rays that are incident approximately from the zenith, hit the atmsophere at the distance ρ from telescope and emit the lights mostly at the altitude h. In this case, $tan\,\delta \approx \rho/h$, and the condition, let us set as $\delta < 60°$, requires that ρ/h is less than 1.7, so that ρ should be less than 8.5 $\sim$ 17 km for $h = 5 \sim 10$ km. The detection area is then 200 km^2 $\sim$ 900 km^2.

SUMMARY AND SCIENTIFIC OBJECTIVES

IACT with a large field of view is available by using refractor to collect Čerenkov lights [4]. Air scintillation lights are also incident into the telescope. By not leaving them as background lights but using as signal, the telescope is given a huge detection area and provides deep survey of energetic γ-rays. At least several tens of photoelectrons are necessary for γ-ray detection, and when the size of the telescope is of $\sim$ 20m aperture, the threshold energy of the telescope will be 50$\sim$100GeV and possibly 100TeV$\sim$1PeV, respectively for Čerenkov and scintillation lights. The raw data of the imaging telescope is contaminated by overwhelming cosmic ray background and does not self-evidently indicate γ-ray signal and its direction. We need to maximize the searching power for hidden sources against a huge amount of data of all sky monitor. It is indispensable to continuously scan the counting rates by a prompt analysis and to search for "interesting directions" that have excess counts. Such prompt scanning will be useful in practice to indicate γ-rays from violently time variable, intense objects like GRB and the emission from the Galactic disc.

Figure 3 presents a view of "the environments of all sky monitor". We expect that the Galactic disc emission is studied well into details. The recent results from VHE γ-ray observation have raised a puzzle, "Where is the proton sources?", revising the long-standing problem of "origin of cosmic rays". The disc emission observed by EGRET in the GeV region is not fully consistent with what is expected from the conventional model of acceleration and propagation of cosmic rays. The energy spectrum as well as its dependence on Galactic longitudes would provide

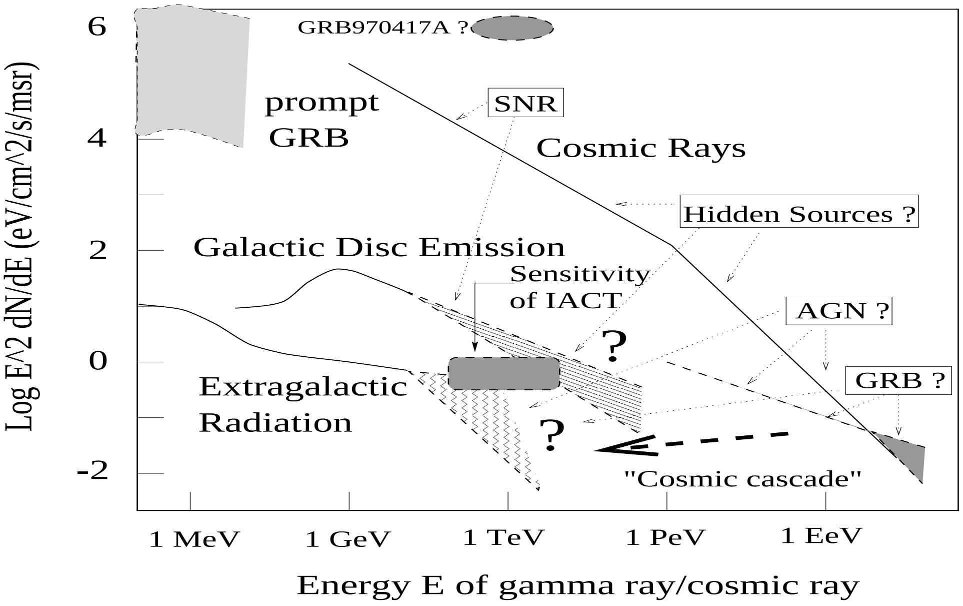

FIGURE 3. Environments of all sky monitor: Looked for in the Heaven is "γ-ray signal from cosmic rays", while the γ-ray signal on the Earth is contaminated by the abundant background of cosmic rays. Energy spectra of cosmic ray, diffuse γ-rays from Galactic disc and high Galactic latitudes are plotted. The fluence in the vertical axis is in the unit of eV cm^{-2} s^{-1} (10^{-3} steradian)$^{-1}$ (*i.e.* plotted is extended emission per 10^{-3} steradian $\approx$ 1/10 of IACT's field of view). The fluence of point-like source, GRB, as well as the IACT sensitivity, is also plotted in this figure, as if they have extension of 10^{-3} steradian, thus the unit in this case to be read as eV cm^{-2} s^{-1}.

constraints on the distribution of the acceleration sites of cosmic rays.

Possibly detectable is the extragalactic diffuse γ-rays from high Galactic latitudes and the emission from the halo of our Galaxy and other nearby galaxies, if they show non-uniformity or granular structure. Recently, speculated and argued about are, as a candidate of the acceleration site of cosmic rays up to the highest energies, violently time-variable object or GRB, and AGN with the hadron jet model assumed. The absorption mean free path of γ-rays, due to production of electron-positron pair in collision with the background radiation, decreases rapidly from $\sim$ 100Mpc at 1 TeV to $\sim$ 10kpc at 1 PeV, and thus the total activities of VHE γ-rays integrated over from nearby objects would manifest themselves in the intensity and shape of energy spectrum of the diffuse emission. Radiation from the distances farther than the absorption mean free path of γ-rays initiates "cosmic cascade" process (in interaction with 2.7K mircrowave background etc.) which eventually produces TeV γ-rays and contributes to the diffuse emission possibly as a granular structure of excess events.

Persistent and intense emission of VHE γ-rays requires expensive energy budget that not many Galactic objects with $\sim 1M_\odot$ are expected to afford. New, unknown populations of γ-ray sources would then be likely to exhibit violent time variability, radiating a great amount of energy in a short time duration. In Figure 3 is plotted the estimated TeV intensity of GRB 970417A which is claimed by Milagrito Detector [7]. Such intense signal from GRB and other hidden sources is detectable above the rate of cosmic ray background.

"Decent" telescope of PeV γ-rays of reasonably large detection area pushes the frontier of γ-ray astronomy to higher energy region, and provides key to testify exotic phenomena, such as the violation of the Lorentz invariance, enabling a clear test, should evidence of γ-rays near 100 TeV energy be found from the objects beyond the conventional absorption mean free path [8].

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