Overview and Potential Prospects for VHE Gamma Ray Astronomy

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During the last decade of years, evidence of TeV γ-rays has been presented from pulsar, supernova remnant and active galactic nuclei, providing a unique way to study the non-thermal high energy sky and opening a window of TeV γ-rays as the highest energy band of electromagnetic radiation. The number of TeV sources is yet about ten, and observation of TeV γ-ray telescope limited to enigmatic, luminous objects in other wavelengths which are presumed to be also bright in TeV band. Such a belief seems to appear not always true, and the major part of the profile of TeV γ-ray sky remains hidden from the observations so far done. To develope new instrumentation of TeV γ telescope is proposed and argued for challenging to uncover the unknown area of TeV γ-ray sky.

KEYWORDS: atmospheric Čerenkov lights, fluorescence lights, gamma-rays, cosmic rays, supernova remnant, pulsar, blazar

§1. Introduction

Astronomy by using VHE (very high energy) γ-rays at TeV energies is still in infancy, when compared with the other longer wavelengths. However, since the time when the signal from the Crab nebula was firmly detected by using the Whipple 10m telescope of imaging air Čerenkov lights,$^{1)}$ the age now exceeds 10 years, and it is not too early to consider about a broad scope of possibilities in the future.

Stereoscopic observation by using a system of multiple imaging air Čerenkov telescopes (IACT) is conceived commonly by several groups as the *standard* way of VHE γ-ray observation in near future. The method is based on (i) the stereoscopic technique of detecting atmospheric Čerenkov lights, improving angular and energy resolutions and rejection power of cosmic ray background, by using (ii) the telescope of size larger than 10m to reduce the threshold energy of detectable γ-rays down to ~ 100 GeV. The system of multiple IACTs has no technically serious uncertainties. It is a promising and steady way of the next generation stage of the current IACT. However, *to be steady* also means that the conditions basically similar to what has affected the existing results continue to constrain the outcomes we expect to have.

When we look back over the history of, for instance, X-ray astronomy, its marvelous progress and the outcomes in the past 40 years owe greatly to the improvement of flux sensitivity by almost 10 orders of magnitude. Deep survey was enabled by developing a variety of different kinds of X-ray detectors; with good angular/energy resolution or having fast data acquisition of time varying data.

Efforts are now being done to reduce the threshold energy of detectable γ-rays by using IACT. It is because we can expect, at lower energies, better statistics, *i.e.,* higher sensitivity to γ-ray flux, or a greater number of TeV sources. Emission of VHE γ-rays is from non-thermal high energy particles accelerated in enigmatic objects. It is one of the motivations of γ-ray astronomy to attempt clarifying the nature and origin of cosmic rays, high energy particles that fill in the Universe. Cosmic rays distribute in the energy range from GeV over TeV to much higher energies with power law spectrum. Thus, TeV γ-ray astronomy is linked to the neighboring higher and lower energy region, *i.e.* PeV and GeV region, as well as even to cosmic rays of energies as high as 10^{20}eV. the direction towards higher energies than TeV is to be kept in mind.

It is necessary and interesting to consider about possibilities other than the standard path of IACTs. With such a *prospect* in mind, let us review in the following section the VHE observations since its *break-through* ten years ago.

§2. Present status of VHE γ-ray observations

2.1 TeV γ-ray sources

The GeV sources as well as PeV ones are likely to emit TeV γ-rays. In 1980's, observations in both of the TeV and PeV energy region presented *evidence* which speculates a signal of transient γ-rays from X-ray close binaries. Retrospectively, however, it was inevitable and reasonable that observation had to be attempted on the Crab nebula, one of the most intense, stable sources of GeV γ-rays and then the breakthrough of TeV γ-ray astronomy took place.

A summary of TeV γ-ray observation is discussed in Table 1. The catalogue of TeV γ-ray sources, for instance presented by T.C. Weekes$^{2)}$ includes objects more than ten, however, remaining as the same with what was presented a year ago in 1999.

The Whipple detection of the Crab nebula was followed by the observation of nearby blazars and the γ-

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ray pulsars and other EGRET to find Mrk 421[3] and PSR 1706-44[4] as TeV γ-ray sources. Observation of EGRET unidentified sources which are associated with SNR have so far failed to detect TeV signal, betraying the expectation that GeV and TeV evidences would confirm the belief that these SNRs are the site of accelerating hadronic cosmic rays. Instead, TeV signal was found from SN1006,[5] which is not in the EGRET catalogue.[6] Similarly, the blazar Mrk 501[7] was not a GeV source of EGRET detection when it was found to be a TeV source.

Pin-pointed observation has been made on the *enigmatic* objects which appear, from the data in other bands, likely to emit TeV γ rays. Accumulation time for observation is likely to become longer to discover newer sources. In the case of Cas A, which was reported[8] recently as a TeV source, the claim is based on 5σ result from 232 hours observation spanning over three years from 1997 to 1999. The flux of 6×10^{-13} cm^{-2} s^{-1} above 1 TeV is as weak as about 3% of the Crab nebula.

Table I. Summary of TeV γ-ray observation.

	100 MeV - 10 GeV	100 GeV - 10 TeV
pulsar	magnetosphere 6 objects (modulated with spin)	pulsar nebula 3 objects (unmodulated)
SNR (shell type)	several associated unidentified sources	3
X-ray binarires	1 (transient)	1?
unidentified	165	not searched
blazar	75	2∼6?
normal galaxy	1	0
gamma ray burst	5	1?
typical intensity of point sources	$\sim 10^{-11}$ (erg cm^{-2}s^{-1})	$\sim 10^{-11}$ (erg cm^{-2}s^{-1})
Galactic plane	6×10^{-8} (erg s^{-1}sr^{-1})	not detected yet $10^{-9} \sim 10^{-8}$? erg s^{-1}sr^{-1}
extragalactic diffuse	@ $\sim 1 \times 10^{-8}$ (erg cm^{-2}s^{-1}sr^{-1})	difficult to observe
$\sum_{\lvert b \rvert<20}$ (Sources)		
pulsars	$\sim 2.5 \times 10^{-9}$ (erg cm^{-2}s^{-1})	$\sim 10^{-11}$ (erg cm^{-2}s^{-1})
others	$\sim 5 \times 10^{-9}$ (erg cm^{-2}s^{-1})	$\sim 10^{-11}$ (erg cm^{-2}s^{-1})

2.2 Comparison with other energy bands

Disimilarity of TeV results to the GeV ones can be indicated over the various types of TeV sources: GeV signal modulated pulsar spin against unpulsed TeV γ-rays; the apparent tendency of different bolometric brightness between GeV and TeV blazars. Thus, the GeV sources are not always useful, and X-rays may sometimes do better to predict TeV γ-ray sources. In fact, Mrk 501 and SN 1006 were listed for TeV observation from their characteristics in X-ray data. However, left unattempted is the most exciting case: the sources that might be brighter in the TeV region than at any other bands.

The spectral energy distribution of the known sources of TeV γ-rays, when plotted over the *entire* bands of electromagnetic radiation, seems consistent with bimodal distribution. The distribution is explained by the electron progenitor for the radiation; synchrotron radiation into radio to X-ray bands and inverse Compton emission into TeV region. The lack, or the flux less than the detection sensitivity, of GeV γ-rays from pulsar nebula PSR1706-44 or supernova remnant SN 1006 is presumably because the GeV energy is located in the middle of the bimodal emission spectrum of the two emission mechanism. The explanation by electron progenitor leads to a consequence that the magnetic field in the emission region is not strong, rather as weak as in the interstellar space. The case of the Crab nebula is rather exceptional because the magnetic field is much stronger and the GeV γ-rays is located just in the transition region of intense synchrotron emission to inverse Compton radiation. The stronger magnetic field would in general lead to brighter synchrotron radiation, however, likely to yield less bright TeV sources.

A systematic study of the EGRET blazars has indicated[9] that the blazars having higher energy of inverse Compton peak, or higher acceleration energy, have less bright bolometric luminosity. The tendency is well consistent with the fact that Mrk 421 is one of the weakest GeV sources of EGRET detection. A long patient period for almost two years was spent by the Whipple group before the episodic outburst[10] was observed in 1997. Outbursts of the two TeV blazars have initiated simultaneous multiband observations. Detection of GeV γ-rays was made during the episodic outburst of TeV γ-rays. adding Mrk 501 to the GeV sources The signals of GeV or TeV γ-rays are from the high activity state of the sources and not from the quiescent state. The current detection limit of TeV blazars is indicated from the case of, for an example, 1ES 2344+514,[11] to be of count rate ~ 1 per minute which corresponds to $\sim 10^{-11}$ erg cm^{-2} s^{-1}.

Our understandings on blazars are to a great extent selection-biased. Time variability of blazar signal is an important information to infer the size of emission region near the presumed massive black hole and to estimate the velocity of the jet. The shortest duration time ever observed in TeV is about 15 minutes of the flare of Mrk 421[12] in 1996. However, the observed time scale of duration of outbursts can be also biased by the detection sensitivity of ≥ 1 per minute. Better sensitivity is crucially important for obtaining more sources and achieving advanced investigation of the high energy phenomena around the central engine of active galactic nuclei.

2.3 What remains for further development

No clear evidence of γ-rays from proton progenitor is obtained yet from any point-like sources. γ-rays from protons is so far evidenced only in the extended emission from the Galactic disc, which shows the *pion bump* around 100 MeV. However, the Galactic disc emission has not been detected yet at TeV energies. A survey over various types of SNRs is necessary to argue about the γ-ray sources of proton progenitor and acceleration mechanism. The intensity of point sources and the disc emission will be proportional to the *residence time* within the emission region of each object. The confinement time in the disc is estimated from cosmic ray data to decrease with energy E as $\sim 10^7$years $\times (E/10GeV)^{-0.7}$. Thus, the point sources having energy spectrum of the canonical power of $\alpha \approx 2$ will become dominant with energy increase[13] against the disc emission of power index of $\alpha \approx 2.7$. The integrated intensity of known Galactic sources is given in Table 1 for GeV and TeV γ-rays. The TeV fluence is by orders of magnitude smaller than GeV one, and are to be compared with the disc emission after correcting for the solid angle of extended emission. The TeV γ-ray telescope has a field of view of $3^\circ \sim 5^\circ$ across and can not use anticounter as in the case of satellite observaton of GeV γ-rays. Thus it is hard to reject the overwhelming background of cosmic rays and the extended γ-rays from the Galactic disc have been so far prevented from detection.

A speculation of transient objects being the origin of cosmic rays[14] are recently argued in place of the conventional belief in supernova remnants as the origin. The relativistic shocks in GRBs are argued as accelerating cosmic rays up to very high energies, even to 10^{20} eV.[15] Such models of GRBs predict VHE γ-ray emission. MILAGRO experiment of a large water tank detector might have detected γ-rays[16] at about TeV energies from GRB 970417A, while IACT has better sensitivity but lacks ability of watching a wide area of the sky for GRBs and has not given any meaningful restriction to GRB models. Observation by IACT hopefully with a wider field of view and a larger rejection factor against the background events is awaited for the study of violently time-variable objects such as γ-ray bursts (GRB) and other objects.

§3. Detection methods and technique

In the breakthrough of ground-based γ-ray astronomy by using IACT, several parameters, which are mutually independent or *accidental* to each other, conspire to set the observation window at $\sim$1 TeV. The mechanism forms the base of IACT method, constraining the current detection of TeV sources.

3.1 Atmospheric Čerenkov lights

The height of the shower maximum of extensive air showers initiated by γ-rays of energy E varies as $log E$ and is ~ 10 km for $E \sim 1$ TeV, giving the transverse spread of atmospheric Čerenkov lights on the ground as large as $\sim$ 100m since the emission angle of Čerenkov lights is about 1°. Thus, the parameters are very weakly dependent of the energy E of incident γ-rays or cosmic rays. The total number of photons emitted by Čerenkov effect is, on the other hand, proportinal to the energy of γ-rays or cosmic rays. A typical telescope of an aperture of several meters has an area of $\sim 10\text{m}^2$, and the area of ~ 10 m^2 can collect ~ 100 photons of atmospheric Čerenkov lights from γ-rays or cosmic rays at about 1 TeV.

The detectable value of photon number flux of γ-rays is a function of the effective detection area. Suppose that the statistically reasonable number of events is ~ 1000, which is required for the statistical fluctuation of the signal against the background rate, and to be accumulated over one day or a few nights observation of $\sim 10^5$sec, and then, the detection area of $A \sim 10^5$ m^2 of single IACT is just sufficient to observe with good significance the flux of $\sim 10^{-11}\text{cm}^{-2}\text{s}^{-1}$. We need a γ-ray source that has this intensity at ~ 1 TeV, and the Crab nebula was proved to be the one.

In addition, the statistical fluctuation of background rate must be smaller than the rate of signal events. The intensity of cosmic rays is $\sim 10^{-5}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ which corresponds to

$$\approx 10^{-8}(\Delta\theta/1^\circ)^2\,\text{cm}^{-2}\,\text{s}^{-1}$$

with angular resolution $\Delta\theta$. The number of background cosmic rays per day is $\approx 10^6(\Delta\theta/1^\circ)^2$ and its fluctuation $\approx 10^3(\Delta\theta/1^\circ)$. The condition of signal being considerably larger than the background is satisfied by $\Delta\theta \sim 0.1^\circ$. The resolution of $\sim 0.1^\circ$ was achieved by using the multi-pixel camera *i.e.* by using IACT, and *the breakthrough* of detecting TeV γ-rays took place.

Now ten years after the breakthrough, we need to improve the sensitivity to detect VHE γ-ray fluxes much weaker than the Crab nebula. However, the detection area of about 300 m across is basically determined by the charactreristics of atmospheric Čerenkov radiation that we can not alter, or impossible to increase as long as we use IACT.

In the case of X-ray astronomy, the starting point of $\sim 100\text{cm}^2$, which corresponds to $100 \times (TeV/keV)^2$ cm^2 $\approx 10^{20}\text{cm}^2 = 10^{10}\text{km}^2$ in TeV region and allows a survey for X-ray fluence deeper than $\sim 10^{-12}$ erg cm^{-2} s^{-1}. However, as shown in comparison with X-ray region in Table 2, even the huge area of 10^8 cm^2 is yet too small, in the case of TeV γ-rays, to gather sufficient number of γ-ray photons from the sources by orders of magnitude weaker than the Crab. Unless the detection area is largely increased, no other improvements might be almost useless.

3.2 Standard approach: stereoscopic technique by multiple telescopes of large size

The detection area can be increased by a straightforwarded way of using many telescopes. Also by going to lower energies, the incident flux of photons increases and significance of detection is improved as long as the energy spectrum follows the power law of $dN/dE \propto E^{-\alpha}$ with α steeper than $2 \sim 3$. Telescopes of larger size, which can detect γ-rays of lower energies, provides us with better statistics or sensitivity from a fixed observation time, Thus, a system of multiple telescopes of the size as large as or even larger than 10m diameter is a *paved* way in front of us. Simultaneous operation of multiple telescope, which are designed to be within a common pool of Čerenkov lights, is expected, in addition, to have a merit of improving energy and angular resolution, background rejection.

3.3 IACT at extreme conditions

Operation of IACT aiming at large zenith angles provides a large detection area, since the lights are emitted at remote distances. The increase of the area accompanies also increase of energy of detectable γ-rays by roughly the same factor. The technique has been applied at $50^\circ \sim 80^\circ$ to detect $\sim$ 50 TeV γ-rays from Crab nebula. However, the image of Čerenkov lights shrinks and detection accuracy tends to deteriorate with increasing zenith angle. We may set IACT located at high altitudes and achieve a lower threshold energy, however with decreasing the effective detection area. These two methods of using large zenith angles and high altitudes provide interesting application of IACT, but not considered to lead to quite a new improvement.

3.4 Better resolution

Table II. Comparison of X-ray and TeV γ-ray detection.

	X-ray	VHE gamma ray
νF_ν	10^{-12}erg cm^{-2}s^{-1}	10^{-12} erg cm^{-2} s^{-1}
flux	10^{-3}cm^{-2}s^{-1}	10^{-12}cm^{-2}s^{-1}
duration T	10^5s	10^5s
area A	10^3cm^2	10^8 cm^2
A T	10^8cm^{2}s	10^{13}cm^{2}s
S = ATF	10^5	10^1
$\Delta t = T/S$	1s	10^4s
$\Delta E/E = \Delta S/S$	1/300	1/3
background B	10^{-2}cm^{-2}s^{-1}sr^{-1}	10^{-5}cm^{-2}s^{-1}sr^{-1}
$\Delta\theta \sim \sqrt{F/B}$	1°	0.01°
		anti counter?
cosmic ray rate B and signal flux F is set to be $\pi(\Delta\theta)^2 B = F$		

Cosmic ray flux B dominates in the counting rate of IACT. Instead of increasing the detection area, weaker signal S of γ-ray flux F from point sources can be made detectable with better angular resolution $\Delta\theta$ by reducing the isotropic bacground of cosmic ray events. The signal to noise ratio is given by $S/N \propto (\Delta\theta)^2$, since $S = ATF$ and $B = ATF\Delta\theta$, and the significance $S/\sqrt{N} = (\sqrt{AT}/\Delta\theta) \cdot (F/\sqrt{B})$, where A is the detection area and T observation time. The condition $S/N = 1$ corresponds to the angular resolution $\Delta\theta \sim 0.01^\circ$ for γ-ray fluc at about 1TeV.

The centroid of the image of Čerenkov light is shifted from the true direction by about $0.5^\circ \approx 0.01$radian. The orientation angle of the elongated image toward the true direction of incident γ-rays is measured in the accuracy of $\sim 10^\circ$, yielding $\sim 10^\circ \times 0.01 \approx 0.1^\circ$, which gives the typical resolution of the current IACT. If an imaging camera of smaller pixel sizes is used for a larger amount of Čerenkov photons than the current IACT ones, the orientation axis of Čerenkov light image can be, in principle, determined in the accuracy as good as 1°, We may then obtain angular resolution of 0.01° better than one arcminute and background free signal,

The current statistics from the flux of 10^{-12} cm^{-2} s^{-1} is able to distinguish the width of line emission as broad as 30% (as explained in the Table), which is comparable to the current energy resolution 20% for γ-rays by IACT.

3.4.1 Wide field of view

Insufficient detection area can be compensated by observing many objects simultaneously, The next generation GeV instrument GLAST improves sensitivity, essentially by using larger field view, by orders of magnitude from the EGRET. The extension of the field of view seems to be most realistic also in the case of IACT for TeV γ-rays.(7) The field of view of IACT is limited by the aberration of reflected lights from the telescope mirror. An optical system of good focusing quality over larger solid angles will provide a much wilder field of view than the current typical value of $\sim 5^\circ$. Such a system can be available from using refraction for focusing lights, since the dispersions while the light travelling against different wavelengths is not serious in the case of Čerenkov telescope.

3.4.2 Use of fluorescence lights

Fluorescence lights are emitted isotropicly, and the detection area can be made much larger than the case of Čerenkov lights. However, the intensity of the lights per unit area is decreased by the factor of $\pi\theta^2/4\pi$, where θ is the emission angle ($\theta \approx$ 1degree (1/60 radian) for atmospheric Čerenkov lights). Thus, the energy of detectable γ-rays must increase by this factor. The current size of IACT is not large enough to detect fluorescence lights, unless γ-ray energy is higher than about 1 PeV. However, much larger aperture of telescope can collect sufficient number of fluorescende photons and, in principle, provide a dramatic increase of detection area as large as 10km × 10km, about three orders of magnitude larger than the current area of atomsopheric Čerenkov lights.(18)

§4. Discussions and summary

The current status of TeV γ-ray observation can be summarized as : (1) Attempts of observing TeV energies have been on the objects that appear bright and enigmatic in other wavelengths of electromagnetic radiation. From the pin-pointed observation by IACT on these candidates selected, the number of TeV sources so far known still remains handful. However, (2) the characteristics of TeV sources look disimilar to GeV ones, and a tendency appears that TeV sources are generally less bright in bolometric luminosity, for example, in the case of blazars. Such objects that are most bright in TeV region, if exist, can be hard to know from the other bands and are left hidden from TeV observation. (3) The known sources are limited to those of the TeV flux as intense as the Crab. Detection of signals from blazars such as Mkr 421 and 501 are biased to episodic high activities of outbursts. In order to have unbiased view of the TeV sky, we need a larger detection area than the current value. (4) Transient sources from unkown directions such as GRBs are left unobserved, however intense the emission might be in a short duration period of time. (5) Cosmic ray interaction with interstellar matter produces most intense γ-ray emission from the Galactic disc, and is considered to extend to the TeV region. However, no positive detection has been successful yet because of the technical limitation of IACT.

The use of multiple IACTs of larger aperture is considered to be the most realistic and promising path that we should take, which, however, does not mean that it is the *only, complete* one. Improvement for detecting weaker fluxes, namely to increase the detection area, is of prime importance to achieve deeper survey of VHE γ-rays. Large sized IACT that the *standard path* exploits to construct will enable us to collect a greater number of Čerenkov photons, providing a potential opportunity of improving angular resolution much better than the current $\sim 0.1^\circ$, resulting in better sensitivity to less intense sources. Detection of Čerenkov lights directly from primary charged particles would become available to distinguish cosmic ray composition19) and in addition to enable a greater rejection power against cosmic ray background for γ-rays,

Once a large aperture exceeding 20 m size is made, it would become realistic to consider about using atmospheric fluorescence lights for TeV to PeV γ-ray observation as the next stage. The wide energy region from TeV to 10^{20} eV remains unexploited for γ-ray astronomy. However, hadronic jet model of blazars20) attributes TeV γ-rays to synchrotron radiation of protons of $\sim 10^{20}$ eV. A telescope having a large field of view by using Flescnel lens is under development by Project OWL or EUSO.21) They aim to detect fluorescent lights from $\sim 10^{20}$ eV cosmic rays by watching the atmosphere from satellite-borne telescope. The optical system can be used to detect Čerenkov lights from VHE γ-rays at TeV energies, if installed on the ground, working as an all sky monitor for TeV γ-rays with a large field of view of $1 \sim 2$ steradian.

Fluorescence lights links, in detection technology, observations of TeV γ-rays with highest energy cosmic rays, which are definitely closely relevant to each other in scientific arguments. Since γ-rays in the ultara high energy region can not travel a long distance, the region is considered as *desert*. Cosmic ray data, if no appearance of GZK cutoff is true, might imply high energy activities taking place in our neighborhood. Radiation higher than PeV energies is then to produce in our neighborhood secondary radiation which is accumulated at $1 \sim 100$ TeV as extragalactic extended emission. It is no less important to provide evidence of denying or confirming exotic speculations,22) which is a unique advantage of using the most energetic radiation.

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