(1) Summary Talk of Padova Workshop

(2) General Remarks on the Special Session on Ground Based Gamma Ray Astronomy at 24th International Cosmic Ray Conference in Rome

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(1) presented in the workshop: “Towards a Major Atmospheric Cerenkov Detector IV for TeV Astro/Particle Physics” (Padova, September 11-13, 1995)

Summary of the Padova Workshop

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Abstract

A significant progress is noted since a series of workshops "Towards a Major Atmospheric Čerenkov Detector" was commenced at Palaiseau in 1992. The number of very high energy gamma ray sources is increasing as well as the number of existing and proposed telescopes. We need to prepare ourselves for further steps to take.

1 Introduction

The “ground”, on which Ground Based Gamma Ray Astronomy at Very High Energy (VHE) is based can be characterised by the energy dependende of detector sensitiviy and VHE gamma ray spectrum as illustrated in figure 1. The flux of VHE gamma rays is outnumbered by cosmic ray background and then detection sensitivity, which is limited by the rate B of cosmic ray background, is proportional to \( \sqrt{B} \sim \sqrt{E^\alpha} = E^{-1.35} \), where \( \alpha \) is the spectral index of cosmic rays. The Crab spectrum at VHE appears to have power index of a value between \(-2.4\) and \(-2.7\). The active galactic nuclei has a spectrum with index around \(-2.0\) at lower energies [1], but the absorption of gamma rays during propagation in extragalactic space steepens and cuts off the spectrum near or below 1 TeV. The spectrum from SNR (Super Nova Remnant) is expected to be \( \propto E^{-2.0 - 2.2} \) [2].

![Figure 1: Gamma ray fluxes and detector sensitivity versus energy.](image)

The sensitivity have been improved by a factor of 100 downward in the figure by the jamging technique of Čerenkov light, having made VHE gamma ray signal such as from the Crab detectable above thns reduced background level. However, many weaker sources may exist still below the detector sensitivity. Since the sensitivity has energy dependence less
steeper than the observed and expected energy spectra of VHE gamma rays, the gamma-ray fluxes above the detector sensitivity is practically only available at lower energies. An atmospheric Čerenkov telescope with lower threshold energy has been and is the main topic of the series of the workshops, “Towards a Major Atmospheric Čerenkov Detector” commenced at Palaiseau in 1992, and now we see a steady progress; the VHE signal from the Crab has been now detected by several Čerenkov telescopes, and more imaging Čerenkov telescopes are proposed to join a network of observation with some at threshold energies lower than 100 GeV.

2 Present status

Beyond discovering more sources

We heard a good news of discovery of a new source, Markarian 501 (a talk by Fegan in 24th ICRC (Rome) preceding this workshop). However, the number of sources of VHE gamma ray flux beyond the current sensitivity is still limited to be as several, and “how many sigmas” is what we are still seriously concerned with.

We generally understand that VHE gamma rays from the Crab are from the inverse Compton process by high energy electrons in the source. It is interesting to know how similar a process to the Crab can explain VHE gamma rays from PSR 1706-44 and other EGRET pulsars such as the Vela [3]. For this purpose, it is of prime importance to discover more VHE sources among other EGRET gamma ray pulsars. On the other hand, a careful study on VHE spectrum suggests that a view of synchrotron photons at lower energies from the same progenitor electrons working as targets of the inverse Compton effect [4] is to be examined in the Crab case [5]. By qualifying VHE data, we would be able to argue about more details of the processes taking place at the source.

By the time of this workshop, several, near to ten, groups have reported detection of the Crab signal, the Crab, indeed, working as a useful “standard candle”. The estimated fluxes by different groups tend to come closer. However, the spectrum at VHE has uncertainty $\Delta \alpha \sim 0.3$ in the index of power, and the energy cutoff beyond several TeV unknown.

Qualifying the data with Large zenith angle technique

The Whipple group has attempted to observe the Crab at large zenith angles (Krennrich, this workshop). The result, with an earlier one by CANGAROO [7], indicate that the large zenith angle observation is quite useful to determine the flux at higher energies than the threshold energy available at the zenith. The energy dependence of sensitivity in figure 1 implies, as combined with a power spectrum of gamma rays which rapidly decreases with energy, that most of detected photons are with energies near at the detector threshold and thus that it is not easy to obtain sufficient data from a wide energy band and to determine the energy spectrum of VHE gamma rays. In the observation at large zenith angles, threshold energy and detection area are increased approximately by a same factor, $A(\theta)$ at a large zenith angle $\theta$. The significance of gamma ray signal $S/\sqrt{B}$ is expressed as $(S_{0}/\sqrt{B_{0}}) \cdot A^{(-\alpha+1)/2}$, $S_{0}$ and $B_{0}$ are the values for measurements pointed at the zenith. By putting $\alpha$ to be $-2.7$ and $A$ to be scaled proportional to energy $E$, the expected sensitivity varies as $E^{(\alpha-1)/2} = E^{-1.85}$, resulting in better sensitivities at higher energies than the case of observation at the zenith.
3 What remains to be answered

Stereoscopic technique

Use of multiple telescopes has been discussed by many for a long time to improve accuracies of observation. The stereoscopic method is expected to be powerful in rejecting background and in resolving arrival direction than single telescope. Analysis by using comparatively crude image parameters from two telescopes (such as “span”) was reported by the Durham group (a talk by Turver this workshop and [6]). The HEGRA group has noted significant signals from Markarian 421 from their two telescopes (a talk in 24th ICRC, Rome), but stereoscopic analysis of these data remains to be reported. The general situation at present is, to my understanding, that we have too many interesting topics and development works of exploiting potential abilities of a single imaging telescope.

Advanced analysis of single telescope data

The parameter “alpha” or “miss” characterizes only one-dimensional knowledge on arrival direction of gamma rays in the image plane. However, the image of Čerenkov light carries information more than what are approximated by the image parameters. A new approach of analysing images (presented by Bohec, this workshop) has shown that two point sources separated by 0.35° can be reconstructed in the two-dimensional image plane by analysing simulated data for the CAT telescope. In order that such an analysis is practically possible, the imaging camera must have a good enough resolving power and small enough systematical errors to measure the detailed structure of Čerenkov image, and an evidence for this in the current camera can be seen in the “asymmetrical parameter” applied to the Crab data of the Whipple group [8].

Single muon which hits a telescope was pointed out to become a very serious background, unless multiple telescopes are used, in observations with threshold energies lowered near to 100 GeV (a talk by Rose, this workshop). However, the advanced analysis method described above may allow the data of single telescope to be lightened the burden of the single muon background.

SNR and extended emission

Efforts for finding gamma ray signals from SNR are so far unsuccessful. However, the features of expected gamma rays from SNR are on a firm base about the energetics and the power index near the value of −2 (explained by Drury, this workshop). Distances to SNR are for an example rather to be examined. It is too early from the recent results in VHE gamma rays to argue about the nature of SNR. The emission from nearby SNR is likely to be spatially extended more than the angular resolution of VHE gamma ray detection. Extended emission of gamma rays merges into background under the current imaging analysis of using “alpha” or “aziwidth”. Either some advanced technique of analysis or stereoscopic observation is necessary.

X-ray binaries and other non-EGRET sources

Clear confirmation of VHE gamma ray emission from X-ray binaries also remains to be done. So far major efforts with imaging telescope have been on EGRET sources to ensure the technique. Several of the X-ray binaries were reported to have persistent emission, which implies “DC excess” detectable with imaging technique at any observation time. Episodic bursts would be now evidenced with high statistical significance as has been experienced on Markarian 421 and 501.
4 Future detectors

Attempt to overlap energy region with satellite detectors is proposed by several talks; imaging telescope with 17 m diameter or one set at a high altitude, and the use of a huge area of reflectors of solar plants; various ways of developing the current technique of Čerenkov telescope were also presented such as about improving quantum efficiency. The EGRET data have shown a variety of types of gamma ray sources. Such a prosperous aspect of the field hopefully extends also to 100 GeV energies. If so, each type of detector can have each “raison d’être” corresponding to different types of source. I wonder if we rather go along a way from “a Major Atmospheric Čerenkov Detector” “Towards Various Atmospheric Čerenkov Detectors”.

Existence of thousands of gamma ray sources at GeV energies if the sensitivity improved may be pointed out from the EGRET result, implying that non-thermal high energy processes are common in many objects, taking place together with other processes. The non-thermal power law spectrum may allow this tendency to extend to higher energies. Thus, closer links to other wavelengths than the present time may be built-in for the future VHE gamma ray astronomy. An invited talk on “Non-thermal processes in X-ray astronomy” (by Prof. Y. Tanaka) was given in a memorial session for late Prof. Bruno Rossi.

It is a pleasure to thank M. Cresti and other local Committee members for organising the successful workshop in Padova – a historical place of Galileo Galilei and of other academical glories.

References


Ground Based Gamma Ray Astronomy

(1) General Remarks on the Special Session

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Abstract

The ground-based gamma ray astronomy has its coming of age currently with 4 sources detected at high significance levels, after experiencing about 30 years history. The energetic gamma rays provide direct means of uncovering high energy non-thermal phenomena at various celestial objects. We need more data with improved sensitivities, and multitudes of such efforts are now under way.

1 Introduction

The Special Session of Ground Based Gamma Ray Astronomy consisted of 5 talks:

(1) General Remarks : T. Kifune (ICRR, Tokyo)
(2) VHE Gamma Ray Sources and Implication : F. Aharonian (Max Planck)
(3) Prospect of Ground-based Techniques
   3-1 Imaging Cerenkov Telescope : M. Cawley (St Patrick's College)
   3-2 Large Area Cherenkov Telescopes : R. Ong (Chicago)
   3-3 Water Cerenkov Detector (MILAGRO) : T. Haines (Los Alamos)

The energy band of electromagnetic radiation higher than several hundred GeV, usually called Very High Energy (VHE) is bound to be ground-based for a large detection area sufficient to detect decreasing flux with gamma ray energy. The number of VHE gamma ray sources is still limited; only 3 sources (Crab [2], Markarian 421 [3] and PSR 1706-44 [4]) are discovered with statistical significance $> 10 \sigma$, added with Markarian 501 [5] from very recent observation. The number of discovered sources is plotted in figure 1 as a function of year, together with those in X-ray and GeV gamma rays. The current status [1] of Ground Based Gamma Ray Astronomy may be too premature to argue about prospect of the future of the field. However, the number of sources is increasing, and the prospect looks bright. The data available so far suggests several
interesting hints for clarifying the high energy processes which take place, as an example, near pulsars. The efforts for inferring implication of the VHE gamma ray data, however of a quite limited size, would be helpful to achieve earlier development of VHE gamma ray astronomy.

2 Present status

The detection of 20 $\sigma$ signal from the Crab Nebula [2] by using an imaging Čerenkov telescope was reported about 5 years ago after almost 30 years efforts for VHE gamma rays. This breakthrough was contemporaneous with the launching of the gamma ray satellite CGRO (Compton Gamma Ray Observatory), and thus observations on the sources [6] from EGRET detector on board CGRO were attempted, followed by discoveries of the other VHE sources. On the other hand, observations in 1980’s were mostly devoted to X-ray close binaries, such as Cyg X-3 and Her X-1. Evidences of VHE gamma rays from these are statistically marginal and based on temporal bursts of observed events. These need to be confirmed by observation with the current telescopes of imaging Čerenkov light.

The situation described above can be seen in the list of the papers presented to the session OG4: About gamma ray pulsars of EGRET detection, the number of papers on the Crab Nebula is 9; 3 papers on Geminga and one paper on other pulsars: About X-ray binaries, 3 papers for cataclysmic variable AE Aquarii and 3 papers each on Vela X-1, Cen X-3 and Cyg X-3: As for extragalactic objects, 3 papers on Markarian 421 and 3 for other AGN (active galactic nuclei): For observation on SNR (super nova remnant), 3 papers.

From a different point of view, the “ground”, on which Ground Based Gamma Ray Astronomy is based can be featured by the energy dependence of detection sensitivity and gamma ray spectrum as illustrated in figure 2. The flux of VHE gamma rays is outnumbered by cosmic ray background. The sensitivity limited by the rate $B$ of cosmic ray background is proportional to $\sqrt{B}$ with energy dependence of $\sqrt{E^{-2.7}} = E^{-1.35}$. The Crab spectrum at VHE appears to have power index of a value between $-2.4$ and $-2.7$. AGN have spectrum with index around $-2.0$ extrapolated from lower energies [7], but the absorption of gamma rays during propagation in extragalactic space steepens and cuts off the spectrum near or below 1 TeV. The spectrum from SNR is expected to be $\propto E^{-2.0-2.2}$ [8].
3 Prospect and implication of recent data

VHE gamma rays are radiated from energetic protons and electrons, which, once escape out of the source region, constitute cosmic rays. Thus, Ground Based Gamma Ray Astronomy is closely related with cosmic ray physics that has a long history; various models of acceleration and propagation of cosmic rays have been argued and discussed as well as about a variety of objects as the origin of cosmic rays. In addition, the EGRET data at GeV energies has given us new insights on pulsars, AGN and other objects. Recent data from radio and X ray astronomy also present hints of non-thermal processes which may suggest VHE gamma ray radiation, such as synchrotron nebula and pulsar wind appearing as a jet of high velocity. Corresponding to such many topics related to VHE gamma rays, there would be many different ways of reviewing the current status of VHE gamma ray astronomy.

However, the Crab is, above all the topics, most important: VHE gamma ray signal from the Crab is detected by several groups near to ten. The Crab is also the object best studied in all the wavelengths. In the Crab nebula, VHE gamma rays are considered to be by energetic electrons boosting ambient photons in longer wavelengths through inverse Compton effect, and the recent data from GeV to TeV has enabled us to argue about the processes in the Crab nebula in detail [9]. VHE gamma rays from the Crab are "DC" not pulsed as in modulation of pulsar period, in contrast to GeV gamma rays. This implies that the VHE emission is from a place distant from the rapidly spinning pulsar. The progenitor electrons of VHE gamma rays have been transported from the pulsar as "pulsar wind" to form a nebula of energetic electrons and radiate VHE gamma rays. It is interesting and important to know if such a process takes place also at other pulsars, which would give estimate how many pulsars can appear as VHE emitter.

Also interesting is VHE gamma rays from SNR, which is a very likely origin of cosmic rays, and some of unidentified EGRET sources contain SNR within the error circle of detection. The efforts so far done have shown no indication of emission at VHE or higher energies. However, it is too early to draw conclusion which suggests to alter the emission model [8] from these unsuccessful results on VHE gamma rays from SNR. Values of various parameters such as distances to SNR have uncertainties. The emission from nearby SNR is likely to be extended more than the angular resolution of VHE gamma ray detection. Extended emission of gamma rays merges into background under the current method of analysis and signals can be easily
missed.

VHE gamma rays from AGN are no less important than those from pulsars and SNR. The two VHE sources, Markarian 421 and 501, are located at the shortest distance among the EGRET AGN. VHE gamma rays suffer from absorption in collision with extragalactic infrared photons by creating an electron-positron pair. The absorption mean free path decreases with increasing energy of gamma rays, and we need to reduce threshold energy of VHE gamma ray detection down to about 100 GeV in order to detect AGN at redshift of 1.

4 Detection method

The number of VHE sources which forms the base of discussing implication of VHE gamma rays is still limited. Thus, the prospect of VHE gamma ray astronomy we try to imagine is also limited by this small number, and it is crucially important how sensitive detectors will be available in near future.

In figure 2, the sensitivity has been improved by a factor of 100 downward in the figure by the imaging technique of Čerenkov light, having made VHE gamma ray signal detectable above thus reduced background level. Many weaker sources may exist still below the detector sensitivity. Since the sensitivity has energy dependence less steeper than the observed and expected energy spectra of VHE gamma rays, the gamma rays are practically only observable at lower energies. Main efforts are, thus, to push down the threshold energy as low as possible, aiming at filling the gap in 30 - 300 GeV region between ground-based and satellite-borne instruments. One possibility is a challenging plan of a huge area of Čerenkov light collector (by using reflectors for existing solar energy plant) outnumbering by orders of magnitude a typical existing Čerenkov telescope. Alternatively, to push down the sensitivity vertically in the figure requires more detection area and time or improvement in distinguishing more efficiently the cosmic ray background. The MILAGRO project utilizes a huge water tank for detecting VHE gamma rays. This has a complimentary merit of 24 hours operation when compared with air Čerenkov technique, and has a closer access to gamma ray bursts.

Acknowledgements

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References


Figure Captions

Figure 1: Number of discovered sources is plotted as a function of year. Names of several satellites which contributed to the increase of the number of sources are given in the figure for X-rays and GeV gamma rays.

Figure 2: Gamma ray fluxes and detector sensitivity versus energy.
fluctuation and other pulsars? Sensitivity before imaging.

Energy

Sensitivity by imaging technique by large zenith angles

SNR Crab and other pulsars?