Early Days of Cherenkov Emission and Milestones

Razmik Mirzoyan

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(Werner-Heisenberg-Institut)
Munich, Germany
1912

In a balloon at an altitude of 5000 meters, Victor Hess discovered "penetrating radiation" coming from space.
Extensive Air Showers
Images of Extensive Air Showers in Cherenkov Light

~ 10 km
~ 120 m

\( \gamma \quad p \quad \text{Fe} \)
Ground-based VHE γ Astrophysics

# of sources discovered by H.E.S.S., MAGIC, VERITAS, Milagro, Cangaroo: ~155
Also sources by Whipple, HEGRA, Durham, Crimea, Potchefstroom, Telescope Array

A total of ~170 reported sources during past 28 years, mostly by IACTs
Cherenkov light: the beginnings

- In a series of publications Oliver Heaviside has calculated and predicted the main features of a special emission when an electron moves in a transparent medium with a speed higher than that of light.

- The work of the genius, who advanced his time by half a century, was not appreciated by contemporary scientists and was forgotten. In 1912 he calculated the geometry and the angle of emission relative to the axis of movement of the charge (1888, 1889, 1892, 1899, 1912a,b).

- Please note that during the end of 19th century scientists believed the space was feeled-in with Ether.
Cherenkov light: the beginnings

- It took almost 50 years until the effect was experimentally discovered and later on got the name Cherenkov.
- Also Sommerfeld studied the problem of a charge moving in vacuum with a speed $v > c$ (1904). The relativistic principles prohibit such a motion in vacuum but in a medium with given $n$ then his equations give valid solution ("sonic boom").
- First observation of ghostly bluish glow of bottles in the dark cellar, containing radium salts dissolved in distilled water, by Marie Curie in 1910 (E. Curie, 1937). It was thought to be a type of fluorescence.

On the left one can see a scan of one of those papers (1926)

Mallet recognised the continuous spectrum of emission that was contradicting the fluorescence theory, but failed to offer any deep explanation.

1924-1928 studying in Voronezh state university.

1930: postgraduate student of Sergej Vavilov at the Institute of Physics of Soviet Academy of Sciences in Sankt-Petersburg (later on FIAN).

Had to find the fluorescence nature of solvents of uranium salts, emitting bluish light.

Big was his surprise that also pure solvents and even water were emitting the annoying background light.
• Initially complaining about his boss: he had to spend >1-1.5 hours in a dark, cold cellar, for accommodating his eyes
• He noticed that the emission is not chaotic, but is related to the track of moving particle.
• 1934-1938 conducting a series of brilliant experiments.
• Obtained doctorate in 1940
• Theory paper by Sergej Vavilov about the possible bremsstrahlung nature of the bluish emission (1934).

• In the same issue a paper by P. Cherenkov about the experiment, that Vavilov refused to co-author.
The Suspicious Emission

- In 1937 Cherenkov succeeded to measure the anisotropy of the emission and submitted it to the journal "Nature".
- "Nature" declined his paper.
- Fortunately "The Physical Review" accepted it.
- In that paper he has mentioned the possibility to measure fast $e^-$.
LETTERS TO THE EDITOR

Prompt publication of brief reports of important discoveries in physics may be secured by addressing them to this department. Closing dates for this department are, for the first issue of the month, the eighteenth of the preceding month, for the second issue, the third of the month. Because of the late closing dates for the section no proof can be shown to authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents.

Communications should not in general exceed 600 words in length.

P.A. Cerenkov
The Physical Institute of the Academy of Sciences U.S.S.R., Moscow
Received June 15, 1937

Visible Radiation Produced by Electrons Moving in a Medium with Velocities Exceeding that of Light

In a note published in 1934 [1] as well as in the subsequent publications [2] [3] [4] the present author reported his discovery of feeble visible radiation emitted by pure liquids under the action of fast electrons (β-particles of radioactive elements or Compton electrons liberated in liquids in the process of scattering of γ-rays). This radiation was a novel phenomenon, which could not be identified with any of the kinds of luminescence then known as the theory of luminescence failed to account for a number of unusual properties (insensitiveness to the action of quenching agents, anomalous polarization, marked spacial asymmetry, etc.) exhibited by the radiation in question. In 1934 the earliest results obtained in the experiments with γ-rays led S.I. Wavilow [5] to interpret the radiation observed as a result of the retardation of the Compton electrons liberated in liquids by γ-rays. A comprehensive quantitative theory subsequently advanced by I.M. Frank and I.E. Tamm [6] afforded an exhaustive interpretation of all the peculiarities of the new phenomenon, including its most remarkable characteristic - the asymmetry.

According to their theory, an electron moving in a medium of refractive index n with a velocity exceeding that of light in the same medium (β > 1/n) is liable to emit light which must be propagated in a direction forming an angle θ with the path of the electron, this angle being determined by the equation:

\[ \cos \theta = \frac{1}{\beta n}, \]

where β is the ratio of the electron velocity to that of light in vacuum.

A successful experimental verification of formula (1) was only performed with water [4] for which, at the moment

![Figure 1: Arrangement of apparatus.](image)

of publication of the above theory, data were already available which had been obtained by visual observations by the method of quenching [7] [8].

We recently performed additional experiments in which the intensity of radiation was recorded photographically, the records being taken simultaneously for all the angles θ lying in a plane passing through the primary electron

beam. The liquid was placed in a cylindrical glass vessel with very thin walls, and the light emitted by the liquid was reflected by a conical mirror in an upward direction to the object glass of a photographic camera as indicated in Fig. 1. An approximately parallel beam of γ-rays, filtered through a 3-mm lead plate, fell on the liquid horizontally. The γ-radiation used was equivalent to that of 794 mg of radium. The considerable thickness of the lead screen, the large aperture of the object glass (f : 1.4) and the long exposure (72 hours) ensured sufficient distinctness of the photographs.
Seen from above the anisotropy of the emission will show up as an arc
Cherenkov light: the beginnings

- 1946: Vavilov (who just became the president of the Academy of Sciences of USSR), Cherenkov, Tamm (head of theory division in FIAN) and Frank obtained Stalin’s prize for their work.

- Vavilov in former USSR was/is usually given higher credit for the effect (which is not clearly justified).

- 1958: Cherenkov, Tamm and Frank were awarded Nobel prize.

- 1964: (rather late) Cherenkov became corresponding member of Soviet Academy of Sciences.
Cherenkov, Tamm and Frank awarded Nobel Prize in 1958

- S. I. Vavilov has passed away in 1951 (after ~10 heart attacks).
- Nobel prize is awarded only to scientists who are alive
Pierre Auger, who had positioned particle detectors high in the Alps, noticed that 2 distant detectors both signaled the arrival of particles at exactly the same time.

Auger had discovered "extensive air showers," showers of secondary subatomic particles caused by the collision of primary high-energy particles with air molecules.
The Very Beginning of Atmospheric Air Cherenkov Telescope Technique

1948

• Patrick Blackett (Nobel prize laureate of 1948: study of cosmic rays using counter-controlled cloud chamber) was the first to mention that there shall be Cherenkov light component from relativistic particles in air showers (mostly e-, e+, µ-, µ+) marginally contributing (~ $10^{-4}$) to the intensity of the light of night sky (LoNS)

• Until that the Cherenkov light has been detected only in solids and liquids
1953

By using a garbage can, a 60 cm diameter mirror in it and a PMT in its focus, Galbraith and Jelly had discovered the Cherenkov light pulses from the extensive air showers.
Light Pulses from the Night Sky Associated with Cosmic Rays

In 1948, Blackett suggested that a contribution approximately 10% of the mean light of the night-sky might be expected from Čerenkov radiation produced in the airscovers by the cosmic radiation. The purpose of this communication is to report the results of some preliminary experiments we have made using a photomultiplier, which revealed the presence of light-pulses of short duration correlated with cosmic radiation.

A photomultiplier was mounted with its cathode at the focus of a parabolic mirror (see diagram, insert). The field of view of this telescope being approximately ±12° from the zenith. The output of the photomultiplier was connected to an amplifier with time differentiation and integration time-constants of 0.038 sec. The amplifier was mounted in a field adjacent to this establishment at the centre of a square array of sixteen Čerenkov-Müller counters (each of area 200 cm²: the sides of the entire array were 180 m in diameter, designed by Cranham for studies of extensive air-showers). The results obtained were as follows.

(a) On the night of September 26th, the pulses were first observed on the oscilloscope and were seen to be nearly constant in time the mean height of the light-pulses was due to the general night-sky illumination. Photographs of the pulses were taken and a pulse height distribution plotted (see graph). With the bias arbitrarily set at three times the night-sky noise the first pulse was recorded in 100 min.

(b) Artificial night-sky noise was then produced by means of a small lamp inside a lid placed over the telescope. In 30 min, no noise build-up pulses were observed at the same bias and gain conditions.

(c) Three-fold coincidence pulses corresponding to light pulses detected by the extended array were used to trigger the Čerenkov-based oscilloscope, and the light pulses (if any) displayed on the Y-plates.

In nineteen such showers there was no evidence of having associated light pulses.

On the night of October 14–15, we decided to trigger the oscilloscope from the light pulses (again selected to be greater than three times night-sky noise) and display the pulses from all the sixteen single counters from the extensive shower array on the Y-plates. Out of fifty time-bases triggered (in 58 min), eighteen had single Čerenkov-Müller pulses at the same point on the time-base; two had a coincidence between two Čerenkov-Müller tubes, one corresponding to three Čerenkov-Müller tubes and one to four Čerenkov-Müller tubes. The rate of observing Čerenkov-Müller pulses on the time-bases associated with light-pulses (when the association is to within 1°) is approximately a thousand times the accidental coincidence-rate. Moreover, the fact that all the Čerenkov-Müller pulses occur at the same point on the time-base and correspond in some instances to more than one counter being discharged strengthens the correlation between them and the light.

(d) On October 22, a night of complete cloud, when the cloud-base was known to be between 4,000 and 9,000 ft., pulses at about half the rate were observed under the same conditions and gain and bias.

The conclusions are: (i) A large fraction of the light pulses observed are correlated with the cosmic radiations; (ii) none of the light pulses may be attributed to spurious effects, for example, high-speed break-down, electronic pick-up or noise pile-up; (iii) from the steepness of the front of the light pulse, it is estimated that the duration of the light pulses is less than approximately 0.005 sec.

The negative result of experiments (b), in which we observed no light pulses on the nineteen time-bases triggered from the showers, may be accounted for by the smaller angle of acceptance for the light by the telescope than for showers by the Čerenkov array.

Some of the light pulses observed may result from relatively soft showers high in the atmosphere radiations rather than light produced by ionization. A series of experiments is planned to investigate the exact nature of the phenomenon.

The above experiments were undertaken following a discussion with Prof. F. M. S. Blackett, to whom we are grateful for his continued interest. We wish to thank Mr. W. J. Whitehouse and Dr. E. Brodrick for their encouragement, and Dr. T. E. Cranham for the use of the extensive shower array.
Gamma-ray Astronomy, the beginning

Seminal paper by Phillip Morrison, 1958

Also proposed at higher energies independently by Giuseppe Cocconi, 1959

AN AIR SHOWER TELESCOPE
AND THE DETECTION OF $10^{12}$ eV PHOTON SOURCES
Giuseppe Cocconi
CERN - Geneva.

This paper discusses the possibility of detecting high energy photons produced by discrete astronomical objects. Sources of charged particles are not considered as the smearing produced by the magnetized plasmas filling the interstellar spaces probably obliterates the original directions of movements.

Here are some numerical estimates.

Magnetic field in the gas shell $H = 10^{-4}$ gauss.
Therefore: $V = 10^{12} \text{eV}$ and $R(10^{12} \text{eV}) = 10^{-3.2} \text{ m}^{-2} \text{s}^{-1}$.

The signal is thus about $10^3$ times larger than the background (2). Probably in the Crab Nebula the electrons are not in equilibrium with the trapped cosmic rays, and our estimate is over-optimistic. However, this source can probably be detected even if its efficiency in producing high energy photons is substantially smaller than postulated above.

The Jet Nebula: $m = 13.5$, $H = 10^{-4}$ gauss.

The signal at the point of detection is probably not fundamentally wrong.
About how could ground-based astronomy profit from the end of the World War-II

- Surplus of otherwise useful things not anymore needed by the militaries!

- Parabolic search-light mirrors of \( \sim0.5\degree-1.5\degree \) angular resolution and 1-2 m in diameter

- Gunmounts, also from military ships, could be used as telescope mounts with readily available drive system
Chudakov and the air Cherenkov technique

- After the presentation of G. Cocconi at Moscow ICRC in 1959, G. T. Zatsepin (from GZK cutoff) has advised Chudakov to measure the predicted gamma-ray sources.
- Chudakov moved to Crimea and easily got first 4, then 8 more parabolic mirrors of 1.5m but of 1.5° angular resolution from militaries securing the Black sea border.
- Very fast a high class installation has been constructed and measurements begun, for almost 4 years.
- A 2-fold and 4-fold (preferred) triggers were used.
Alexander Chudakov and the Cherenkov Technique for Gamma Ray Astronomy

Crimea Experiment 1959-1965, Chudakov, et al., (SNR, radio galaxies)

Tuesday 23rd May 2017, SPSAS School, Sao Paulo

Razmik Mirzoyan, Max-Planck-Institut für Physik: Early Days of Cherenkov Emission
A serious experimental work has been performed by this team. The technique and the instrument were well-understood, below some excerpts from a paper from 1964.
• A multitude of sources have been observed and serious statistical treatment of data has followed

• Except for some small fluctuations no significant flux has been observed $\geq 3.5-5$ TeV, Flux upper limit: $5 \times 10^{-11}$ ph/cm$^2$/s

• They turned down the too optimistic prediction of Cocconi about 1000:1 S/N
Cherenkov Technique used for Gamma Ray Astronomy

1st Gen. Atmospheric Cherenkov Telescope

Glencullen, Ireland
~1962-66

Univ. College, Dublin
group led by Neil Porter
(in collaboration with J.V.Jelley)

(quasars (AGN), variable stars)

Figure 3. **Left:** Neil A. Porter (1930-2006) (Photo: D.J.Fegan) **Right:** The second ground-based gamma-ray telescope; the British-Irish experiment at Glencullen, Ireland c. 1964; the telescope consisted of two 90 cm searchlight mirrors on a Bofors gun mounting. The experiment was led by Jelley and Porter.
1st Smithsonian venture into VHE gamma-ray used Solar Furnace at Natick, MA ~ 1965-6. Gamma-ray Astronomy Group led by Giovanni Fazio

Tuesday 23rd May 2017, SPSAS School, Sao Paulo

Razmik Mirzoyan, Max-Planck-Institut für Physik: Early Days of Cherenkov Emission
The pioneer of gamma astronomy

Work on the Mt. Hopkins Observatory proceeds at an astonishing pace. The laser and Baker-Nunn systems are now installed and operating and the large optical reflector is scheduled to arrive by the end of next month. In preparation for the LOR installation, Trevor Weekes (above, left) and George Rieke have conducted seeing tests with two movable searchlight reflectors. Look carefully – some outcroppings at the base of Mt. Hopkins are visible upside-down in the reflector.
A SEARCH FOR DISCRETE SOURCES OF COSMIC GAMMA RAYS OF ENERGIES NEAR $2 \times 10^{12}$ eV

G. G. Fazio and H. F. Helmken
Smithsonian Astrophysical Observatory and Harvard College Observatory, Cambridge, Massachusetts

G. H. Rieke
Mount Hopkins Observatory, Smithsonian Astrophysical Observatory, Tubac, Arizona, and Harvard University, Cambridge, Massachusetts

AND

T. C. Weekes*
Mount Hopkins Observatory, Smithsonian Astrophysical Observatory, Tubac, Arizona

Received September 3, 1968

ABSTRACT

By use of the atmospheric Čerenkov nightsky technique, a study has been made of the cosmic-ray air-shower distribution from the direction of thirteen astronomical objects. These include the Crab Nebula, M87, M82, quasi-stellar objects, X-ray sources, and recently exploded supernovae. An anisotropy in the direction of a source would indicate the emission of gamma rays of energy $2 \times 10^{12}$ eV. No statistically significant effects were recorded. Upper limits of $3-30 \times 10^{-11}$ gamma ray cm$^{-2}$ sec$^{-1}$ were deduced for the individual sources.
Cherenkov Shower Imaging using Image Intensifiers (1960-65) and Stereo Detectors (1972-76)

Image Intensifier Pictures of Cherenkov light Image from Cosmic Ray Air Shower. On short time-scale images are brighter than bright star (Vega). Work by David Hill (M.I.T.) and Neil Porter (U.C.D.) in 1960

Josh Grindlay demonstrates value of stereo imaging with two-pixel system (Double Beam Technique) at Mt. Hopkins and Narrabri (1972-76)

Figure 5. **Top:** Image Intensifier used by Hill and Porter to record the images of cosmic ray air showers. **Bottom** Images of the night-sky triggered by an ACT (left) and triggered randomly (right). The field of view was ±12.5°.
Victor Zatsepin, born in 1928

In 1960‘s Victor Zatsepin well-understood all the main features of the air Cherenkov technique.

I learned from him that in 1960‘s he was long seriously considering a key question about how one could measure multiple images of showers (which kind of cameras can do it?). He performed simulations of air showers in 1961-64 (were there computers available, really?)

• „URAL“ was the name of the russian computer that was operated by a specially trained staff.
CONCLUSION

The calculations that have been made enable us to draw the following conclusions:

1. Since the maximum intensity of the light from a shower does not coincide with the direction of arrival of the primary particle, in researches in which the determination of the angular coordinates of the primary particle is made by photographing the light flash from the shower one should seek improved accuracy in this determination by photographing the shower simultaneously from several positions.

2. If the distance from the axis of the shower to the detector is determined from independent data, then an analysis of the shape of the light flash from the shower and its total intensity gives information both about the initial energy of the primary particle and about the position in the atmosphere of the maximum of the shower, and can thus be used for the analysis of fluctuations in the development of showers in the atmosphere.

In conclusion I regard it as my pleasant duty to express my gratitude to A. E. Chudakov for suggesting this topic and for helpful discussions.
Arnold Stepanian and his 1st imaging “stereo” telescopes: GT-48 in Crimea
The publications of the Crimean group led by Arnold Stepanian

<table>
<thead>
<tr>
<th>Publications</th>
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An array of ACIT’s was first proposed in 1984 (prior to the detection of the Crab Nebula).

This is the configuration that was later adopted for VERITAS.
Some key developments

- 70-80’s: plenty of „discoveries“ on 3-4 σ level
- M. Hillas: „A physicist‘s apparatus gradually learns what is expected of it (blame the apparatus for a dog-like desire to please)“
- Charge concentration is a good parameter (>75% charge is concentrated in 2 pixels)
- Plyasheshnikov, Bignami (1985) showed „α“ is a useful parameter
- La Jolla, 1985: Michel Hillas suggested to use the „Hillas“ parameters
- 1989: Whipple discovers 9σ signal from Crab !!!
The Pioneer Trevor Weekes and his 10m Ø Whipple telescope gave birth to γ-ray astrophysics: 9σ from Crab Nebula in 1988!

„If a telescope can within a few s evaporate a solid piece of steel, it can also measure gamma rays“ ;-)
We now turn to a discussion of the 1986 observations of Hercules X-1 in which three groups apparently observed the same anomalous frequency, which was 0.16% higher than the neutron star spin frequency. In table 5, the three observations are summarized.

Table 5. 1986 Observations of Hercules X-1 at an anomalous frequency

<table>
<thead>
<tr>
<th>Observatory (Ref.)</th>
<th>Energy</th>
<th>Frequency</th>
<th>Reported Prob.</th>
<th>Prob. (including dc excess)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haleakala (20)</td>
<td>1 TeV</td>
<td>0.80911</td>
<td>0.7x10^{-2}</td>
<td>0.7x10^{-2}</td>
</tr>
<tr>
<td>Whipple (21)</td>
<td>1 TeV</td>
<td>0.8092</td>
<td>0.9x10^{-2}</td>
<td>0.3x10^{-2}</td>
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<tr>
<td>Los Alamos (22)</td>
<td>100 TeV</td>
<td>0.80927</td>
<td>0.2x10^{-4}</td>
<td>0.2x10^{-3}</td>
</tr>
</tbody>
</table>

What is the overall significance of these three detections? If we treat them simply as three independent tests of the same (no-signal) hypothesis, then they can be combined using Fisher’s test as described by Eadie et al. (1971)\textsuperscript{26}. This test does not make use of the information that all frequencies were the same and therefore it tends to overestimate the chance probability; the \textit{ad hoc} nature of the search range used by all three groups (±0.3%) tends to increase it. An implicit assumption is that Hercules X-1 was not being observed by any other groups in 1986 using detectors of comparable sensitivity, so that the three observations constitute the total set of observations of this source. Unreported nondetections make it difficult to assess the overall significance, but would in general decrease the significance. If we restrict our attention only to 1986 (\textit{a posteriori}), and assume there are no significant nondetections during this interval, the chance probability is calculated to be less than 10^{-6}. Taken at face value it would appear that Hercules X-1 was a source of TeV/100 TeV emissions in May-July 1986. However, \textit{a posteriori} probabilities are dangerous and are best treated as a hypothesis for further tests. As time continues with no confirmation of this anomalous frequency (Gupta et al. 1990\textsuperscript{27} notwithstanding) then the impact of this combination of observations becomes weaker.
There were plenty of reports on somehow mysterious gamma sources.
VHE $\gamma$ workshop at 22nd ICRC, Dublin, 1991

Final Program for the Very High Energy Gamma Ray Workshop

Wednesday Evening, August 14, Dublin

Chairman: J.V. Jelley

(a) Atmospheric Cherenkov Telescope Sensitivities.

<table>
<thead>
<tr>
<th>Speaker</th>
<th>Group</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. Raubenheimer</td>
<td>Potchefstroom</td>
<td>Yes</td>
</tr>
<tr>
<td>B. S. Acharya</td>
<td>Tata/Pachmari</td>
<td>Yes</td>
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<tr>
<td>No representative</td>
<td>Durham/Karrabri</td>
<td>No</td>
</tr>
<tr>
<td>G. Sembrowski</td>
<td>Haleakala/South Pole</td>
<td>Yes</td>
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<tr>
<td>P. Goret</td>
<td>Saclay/Themis</td>
<td>No</td>
</tr>
<tr>
<td>G. Thornton</td>
<td>Adelaide/Woomera</td>
<td>Yes</td>
</tr>
<tr>
<td>P. Edwards</td>
<td>Tokyo/Canguroo</td>
<td>Yes</td>
</tr>
<tr>
<td>R. C. Lamb</td>
<td>Iowa/Whipple</td>
<td>Yes</td>
</tr>
<tr>
<td>A. A. Stepanian</td>
<td>Crimean</td>
<td>Yes</td>
</tr>
<tr>
<td>W. Stamm/A.K. Konopelko</td>
<td>Yerevan/Hโครงการ</td>
<td>No</td>
</tr>
</tbody>
</table>

(b) Observing Programs, GRO Overlap (No discussion)

| N. Gehrels, GRO Project Scientist | GRO Status and Program | Yes |

Please note that the Whipple Observatory group has agreed to distribute information pertaining to GRO that is of interest to ground-based gamma-ray observers by e-mail (this includes non-GRO specific programs that may be of interest to the community); we will be happy to include you on the e-mail distribution if you will send us your address. Our BITNET address is "GAMMA@ARIZONA."

Thanks for helping make the workshop a success; from the large attendance there is obviously a lot of interest in the topic.

Trevor C. Weekes

Sept. 11, 1991
2. ENERGY THRESHOLD

(a) how defined: defined as the average energy of a gamma ray event to trigger the telescope
(b) how estimated: The average trigger rate (per minute) for the source direction is obtained from the data. Using the well measured Cosmic ray spectrum, this rate is converted to the Cosmic ray energy threshold. The relevant solid angle factor and the average zenith angle are used as inputs to this calculation. Finally, the gamma ray threshold is taken as half the Cosmic ray energy threshold.

3. COLLECTION AREA

(a) how defined: defined to be within the radius of 100 meters with the telescope as the centre.
(b) how estimated: circles of 100 meter radius are drawn around each telescope. The collection area for the whole array is computed considering the fact that some area will be common to all telescopes.
THE UNIVERSITY OF ADELAIDE'S VHE GAMMA RAY TELESCOPE AT WOOMERA (aka Bigrat)

**Description**
The Woomera telescope is located at $31^\circ 06'\ S, 136^\circ 47'\ E$ at an elevation of 160m. It consists of three twelve square metre composite mirrors on a common alt-azimuth mount. At each focus (f=2.7m) there are three 51mm photocathodes providing a $\sim 2^\circ$ field of view. The tubes are arranged in a triangle with the centroid on axis. The anode signals are ac-coupled, without amplification, to discriminator inputs. The discrimination level is 25 photo-electrons (nominal). We currently run the tubes at $\sim 2-3$ kHz singles rates on the night sky, padded to 5 kHz by computer controlled LEDs. An event trigger is formed by a triple coincidence between the corresponding tubes at the three foci. The vertical trigger rate is $\sim 7$ Hz.

**Energy threshold**
As our definition of $E_{th}$ we use the modal energy of triggering showers from an $E^{-2.1}$ differential spectrum of Hillas Monte Carlo gamma-rays. For vertical showers

$$E_{th} = 500\text{GeV}$$  \hspace{1cm} ($E_{min} = 800\text{GeV}$)

**Collecting area**
We do not explicitly define the collecting area. A value can be calculated by requiring consistency between the event rate, the field of view and on a geometry (see next item).

**Energy threshold**

An energy threshold at the zenith of $\sim 500\text{GeV}$ is believed possible, depending on the final triggering conditions. This corresponds to an event rate of $\sim 10$ Hz.

$$A_e \approx 1.1 \times 10^9 \text{cm}^2$$  \hspace{1cm} (i.e. $R = 190\text{m}$)

where $I_{CR}$ is the cosmic ray flux and $S/B$ is the ratio of the signal to the cosmic ray background.

**Background rejection/ Future plans**
We currently employ no background rejection techniques but we are about to install a 37 pixel camera in place of one of the detector triplets. This should be in place by December 1991. We are experimenting with a pulse shape digitizing system which should provide some gamma/nucleon discrimination.

**References**
Protheroe R.J., 1987, 20th ICRC, 8, 21

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THE CANGAROO COLLABORATION 3.8m TELESCOPE AT WOOMERA

**Description**
The 3.8m telescope is located 100m east of the University of Adelaide telescope (Bigrat) at $31^\circ 06'\ S, 136^\circ 47'\ E, 160$m a.s.l. The 3.8m telescope is a composite mirror on a alt-azimuth mount. The central 1.7m diameter section of the mirror is made from aluminized duraluminium. The six outer segments are canigen coated aluminium alloy. In the focal plane (f=3.8m) is an imaging camera of (64/1256/900) photomultipliers, providing an aperture of $3.2^\prime/4.0^\prime$ diameter. The anode signals are amplified with a gain of 100, allowing low, stable tube gains, before discrimination. A specially designed circuit containing 16 channel amplifiers, discriminators, ADCs, TDCs and single count scalers has been developed. The TDCs aid in night sky background rejection. An event trigger is formed from analog sums and hit...
February 1985
Yerevan Physics Institute
Proposal for 5 imaging Cherenkov Telescopes:
The number „0“ workshop on IACTs took place in Crimea in 1989 (before the 1st in Paris in 1992)

Proceedings of the International Workshop on

VERY HIGH ENERGY GAMMA RAY ASTRONOMY

Crimea, USSR

April 17 - 21, 1989

Edited by

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Crimean Astrophysical Observatory, USSR

D.J. Fegan
University College, Dublin, Ireland

M. F. Cawley
St. Patrick’s College, Maynooth, Ireland

ČERENKOV IMAGING TÉV GAMMA-RAY TELESCOPE


Yerevan Physics Institute, USSR

Crimean Astrophysical Observatory, USSR

Abstract

A Čerenkov imaging telescope being under construction for investigation of TÉV primary γ-rays is described.

The present stage of investigations of cosmic VHE and UHE γ-rays is characterized by high requirements to the reliability of flumes from point sources as well as to identification of γ-events. Development of the background-suppressing techniques seems the most promising way to achieve these aims. In the energy range 10^15-10^19 eV, the main hopes are connected with the possibility for an analysis of the Čerenkov radiation images of atmospheric showers [1]. Efficiency of this method has been successfully demonstrated recently by detection of γ-ray flumes at the 9σ level from the Crab Nebula with the Whipple observatory 10-meter imaging Čerenkov γ-ray telescope [2].

In 1989, at the cosmic ray station of Yerevan Physics Institute, near the Byurakan optical station (40°15' N latitude and 44°30’ E longitude) at an altitude of 1900m, we have begun the construction of an atmospheric Čerenkov imaging telescope, which will be equipped by an equatorial mount. The main parts of the telescope are successfully tested and now we are going to mount the installation.

The characteristics of the telescope are presented below:

- The equatorial mount will be digitally driven by stepping motors through a gear drive. Each motor will be under mini-computer control. Each axis will be equipped with a shaft encoder, the angular resolution of which is 1.2 minutes of arc. The tracking accuracy of the telescope will be 3.0 minutes of arc.

- The 3-meter Čerenkov reflector of the telescope consists of 19 separate 60-cm round glass mirrors with a total collection area of 5.3 m². Each of the reflector facets is a spherical mirror with a curvature radius of 10m. These facets are independently mounted on an almost spherical frame with a 5-meter radius. Thus, the focal length of the reflector is 5 meters.

- The mirrors are made in the optics department of the Yerevan Physics Institute pilot production. The 20mm-thick slabs, 60cm in diameter, are machined, including rounding, roughing, grinding and polishing. Then on their front surface an aluminum layer and a specially chosen protective coating are deposited by evaporation in vacuum. The coating chosen provides a rather high reflectivity, about 80% at 400nm, and long-term serviceability under severe weather conditions. The dependence of mirror reflectivity upon the incident light wavelength is presented in fig.1. The upper curve corresponds to the central region and the lower one to the edge of the mirror. The measurements have shown that the mirrors have an angular resolution of 0.20 seconds of arc. Such a high quality of mirrors is very important, especially for further improvement of the
The 1\textsuperscript{st} telescope (of 5 planned) we’ve built: 1989

Nor Amberd cosmic ray Station, mount Aragats, 2000 m a.s.l., Armenia
Proposal for Imaging Air Cherenkov Telescopes in the HEGRA Particle Array

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ELECTRON DETECTORS: 1 m² scintillation counters for particle density and fast-timing measurements (2 PM's each), with 5 mm of lead for photon conversion.

- 37 detectors in operation since July 1988 (University of Kiel)
- 159 additional detectors, 90 of them in operation since July 1989 (MPI Munich together with University of Madrid)
- 49 further detectors to increase the detector density in the centre of the array, planned for 1991 (University of Hamburg)

49 MUON DETECTORS: 15 m² each, consisting of sandwiches of Geiger tube and absorber layers, planned for 1991/92 (University of Wuppertal together with University of Kiel)

49 CHERENKOV-LIGHT DETECTORS: each consisting of a 20 cm diameter PM and a light-collecting cone, planned for 1991 (MPI Munich together with University of Madrid)

5 CHERENKOV TELESCOPES: 3 m in diameter with 19 mirrors and 37 PM's each, imaging technique, planned for 1991/92 (Yerevan Institute of Physics together with MPI Munich and University of Kiel)

Fig. 1: Status and planned extensions of the HEGRA detector array.
The 1st telescope of HEGRA, the CT1 (installed spring 1992)

CT1 started to collect data in summer 1992
The 1st signal from Crab Nebula fall 1992

CT2 – CT6: 5 more telescopes were built until 1997.

2 x larger reflector, 1997

Tuesday 23rd May 2017, SPSAS School, Sao Paulo

Razmik Mirzoyan, Max-Planck-Institut für Physik: Early Days of Cherenkov Emission
Results of Monte Carlo studies on the performance of the 5 telescope system were published in 1993. Although we overestimated the gain in sensitivity (compared to a single telescope), we clearly understood the strong background rejection feature of the multiple telescopes.

1. Introduction.

So far all observations of primary gamma rays at $E = 1$ TeV have been made with Air Cherenkov Telescopes (ACT). In the foreseeable future this technique will dominate at least at energies $E < 10$ TeV.

One of the most remarkable features of the ACT's is their high rate capability. For collection area $S_{eff} \geq 3 \times 10^4 \text{cm}^2$, easily achieved by simple ACT, the counting rate of VHE gamma rays from the Crab Nebula should be higher than 0.1 events per minute. However, this important feature can acquire its practical significance only in the case of effective suppression of the background induced by the proton–nuclear component of the primary cosmic radiation. Different ways for cosmic ray background rejection were proposed (for review see, e.g., Weekes, 1988); however at present only the so called imaging technique is realized as a powerful method for significant improvement of the sensitivity of detectors in VHE gamma ray astronomy. The application of the multichannel Cherenkov light receiver in the focus of the high quality optical reflector gives a possibility to separate gamma ray– and proton-induced showers, analyzing the...
The HEGRA detector, including 6 air Cherenkov imaging telescopes
Location: ORM @ La Palma
Operation 1992 - 2002
Beginning of large-size telescopes

- A 10m² telescope has a threshold of \(\sim 1\text{TeV}\)
- Since from the beginning it was a common belief that the threshold of a Cherenkov telescope
  \[ E_{\text{thr}} \sim \sqrt{1/A_{\text{mirror}}} \]
- That was suggesting that one needs a \(A_{\text{mirror}} \sim 10^4 \text{m}^2\) for measuring few 10's of GeV; \(\rightarrow\) the only seeming solution: use huge solar power plants for air Cherenkov

- In 1994 I understood that the above relation is wrong for an imaging telescope. It is simply
  \[ E_{\text{thr}} \sim 1/A_{\text{mirror}} \]
Beginning of large-size telescopes

- After that started looking for a telescope with $A_{\text{mirror}} \geq 200 \text{ m}^2$. Soon found the 17m solare telescope of German DLR in Lampoldhausen near Stuttgart, the prototype of MAGIC

- In fall 1994 we performed a feasibility study for a $E_{\text{thr}} \sim 40 \text{ GeV}$

- It became clear: there was a very strong background at several tens of GeV $\Rightarrow$ Multiple telescopes were needed.
VERITAS, H.E.S.S. & MAGIC: the triumphal procession of VHE $\gamma$-astro-physics is continueing
Outlook: the next 5-7 years

Next generation VHE $\gamma$ ray Observatory: CTA

MAGIC Phase II

CTA

HESS Phase II (HESS + 28m Telescope)

Cherenkov Telescope Array
1000's of sources will be discovered

$\sim$1400 scientists
$\sim$130 institutions

Astronomers in EU

JAPAN, US

Razmik Mirzoyan, Max-Planck-Institut für Physik: Early Days of Cherenkov Emission