Beginnings of the Atmospheric Air Cherenkov Technique

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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 movs 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
- 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 (1888, 1889, 1892, 1899, 1912a,b)
- 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 luminescense.

RADIOACTIVITÉ. — *Étude spectrale de la luminescence de l'eau et du sulfure de carbone soumis au rayonnement gamma.* Note [1] de M. **L. Mallet**, présentée par M. Ch. Fabry.

Dans une Note publiée aux *Comptes rendus* [2] nous signalions que l'eau et certaines substances organiques exposées aux rayons γ des corps radioactifs émettent une luminescence blanche. L'étude photographique de cette luminescence à l'aide d'écrans de verre, de quartz et de sel gemme nous avait permis de supposer que cette lumière devait contenir des radiations s'étendant dans l'ultraviolet.

L'étude spectrographique de ce rayonnement très faible aurait été impraticable avec les appareils ordinaires. J'ai pu la mener à bien au moyen d'un spectrographe très lumineux [3] construit sur les indications de M. Ch. Fabry. La chambre photographique de cet appareil est munie d'un objectif ayant une ouverture égale à F/2 (objectif Taylor-Hobson), dont la distance focale est de 108^{mm} et dont, par suite, l'ouverture utile est de 54^{mm}. L'appareil est disposé de telle manière que l'on puisse utiliser divers trains de prismes, pour changer la dispersion ; je me suis servi de deux prismes en flint, de 30°, dont l'un reçoit la lumière sous l'incidence normale, tandis que l'autre est utilisé sous émergence normale. La lentille du collimateur est une simple lentille achromatique, d'ouverture F/10, ayant par suite 50^{cm} de distance focale. L'appareil ainsi disposé donne des spectres peu dispersés mais très lumineux ; on peut sans difficulté, obtenir les spectres de corps faiblement phosphorescents ou fluorescents.

Nous avons pris comme source de rayonnement γ deux tubes de verre contenant chacun 250^{mg} de radium élément (sous forme de SO^4Ra) qui ont été placés dans une gaine de 2^{mm} de plomb. Le rayonnement émergeant était constitué par des rayons γ, sans aucun rayonnement β primaire. Le foyer radioactif a été placé, soit dans un récipient de bois muni d'une fenêtre de celluloïd et rempli d'eau distillée, soit dans un récipient en pyrex, substance qui présente une luminescence propre négligeable.

Nous avons exposé le récipient contenant l'eau devant la fente du spectrographe, dont la largeur a pu être réduite à $0^{mm},2$ sans augmenter exagé-

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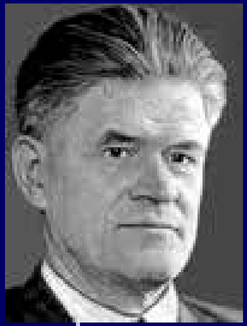
(1) Séance du 17 juillet 1928.
(2) *Comptes rendus*, 183, 1926, p. 274.
(3) Cet appareil sera prochainement décrit dans un autre recueil.

French scientists M.L. Mallet
published 3 articles on the bluish glow (1926-1929).

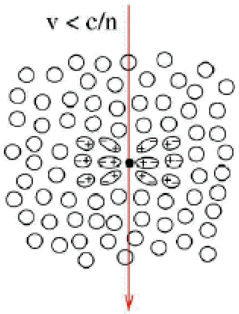
On the left I show a scan of one of those papers (1926) published by Mallet (later on Cherenkov effect)



Cherenkov light: the beginnings

- Pavel Cherenkov: born July 28th 1904 in a poor peasant family village Novaya Chigla, Voronezh province.
- 1924-1928 studying in Voronezh sate university.
- 1930: postgraduate student of Sergej Vavilov at the Lebedev‘s Institute of Physics of Soviet Academy of Sciences (later of FIAN).
- 1934-1938 conducting a series of brilliant expeirments.
- Complaning about his boss: he had to spend 1-1,5 hours in a dark, cold cellar, for accomodating his eyes
- Obtained doctorate in 1940

Cherenkov Effect

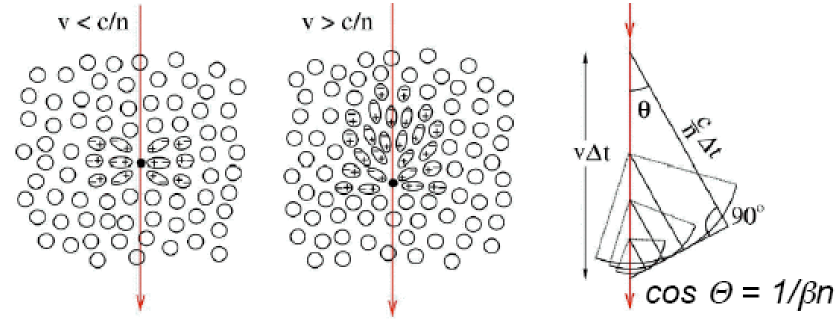


Medium, refractive index n

Charged particle with v < c/n traverses medium
==> local, shorttime
polarization of medium

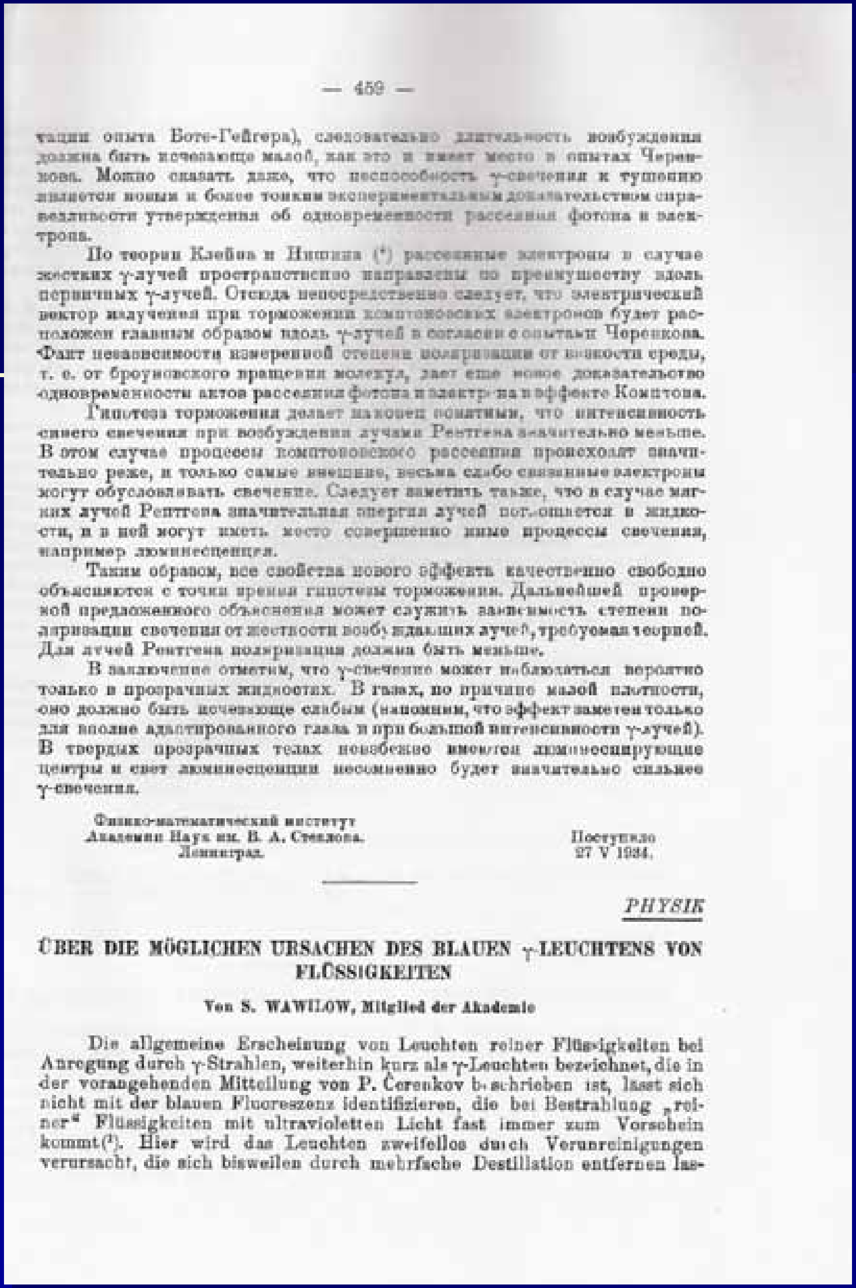
Reorientation of electric dipoles results in (very faint) isotropic radiation

Cherenkov Effect



Similar to sonic boom if v > $c_{acoustic}$

v > c/n
==> radiation from different points along the trajectory arrive in phase within narrow light-cone at the observer ==> bright light



— 459 —

тации опыта Боте-Гейгера), следовательно длительность возбуждения должна быть исчезающе малой, как это и имеет место в опытах Черенкова. Можно сказать даже, что неспособность γ-свечения к тушению является новым и более тонким экспериментальным доказательством справедливости утверждения об одновременности рассеяния фотона и электрона.

По теории Клейна и Нишины (*) рассеянные электроны в случае жестких γ-лучей пространственно направлены по преимуществу вдоль первичных γ-лучей. Отсюда непосредственно следует, что электрический вектор излучения при торможении комптоновских электронов будет расположен главным образом вдоль γ-лучей в согласии с опытами Черенкова. Факт независимости измеренной степени поляризации от вязкости среды, т. е. от броуновского вращения молекул, дает еще новое доказательство одновременности актов рассеяния фотона и электрона в эффекте Комптона.

Гипотеза торможения делает наконец понятным, что интенсивность синего свечения при возбуждении лучами Рентгена значительно меньше. В этом случае процессы комптоновского рассеяния происходят значительно реже, и только самые внешние, весьма слабо связанные электроны могут обусловливать свечение. Следует заметить также, что в случае мягких лучей Рентгена значительная энергия лучей поглощается в жидкости, и в ней могут иметь место совершенно иные процессы свечения, например люминесценция.

Таким образом, все свойства нового эффекта качественно свободно объясняются с точки зрения гипотезы торможения. Дальнейшей проверкой предложенного объяснения может служить зависимость степени поляризации свечения от жесткости возбуждающих лучей, требуемая теорией. Для лучей Рентгена поляризация должна быть меньше.

В заключение отметим, что γ-свечение может наблюдаться вероятно только в прозрачных жидкостях. В газах, по причине малой плотности, оно должно быть исчезающе слабым (напомним, что эффект заметен только для вполне адаптированного глаза и при большой интенсивности γ-лучей). В твердых прозрачных телах неизбежно имеются люминесцирующие центры и свет люминесценции несомненно будет значительно сильнее γ-свечения.

Физико-математический институт
Академии Наук им. В. А. Стеклова.
Ленинград.

Поступило
27 V 1934.

PHYSIK

ÜBER DIE MÖGLICHEN URSACHEN DES BLAUEN γ-LEUCHTENS VON FLÜSSIGKEITEN

Von S. WAWILOW, Mitglied der Akademie

Die allgemeine Erscheinung von Leuchten reiner Flüssigkeiten bei Anregung durch γ-Strahlen, weiterhin kurz als γ-Leuchten bezeichnet, die in der vorangehenden Mitteilung von P. Čerenkov beschrieben ist, lässt sich nicht mit der blauen Fluoreszenz identifizieren, die bei Bestrahlung „reiner" Flüssigkeiten mit ultravioletten Licht fast immer zum Vorschein kommt(¹). Hier wird das Leuchten zweifellos durch Verunreinigungen verursacht, die sich bisweilen durch mehrfache Destillation entfernen las-

Paper by Sergej Vavilov about the possible bremsstrahlung nature of the bluish emission from 1934

P.A. Cerenkov Phys. Rev. **52,** 378 **1937**

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. Wawilow [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

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[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 ($\beta > 1/n$) 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:

$$\cos\theta = 1/\beta n, \qquad (1)$$

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

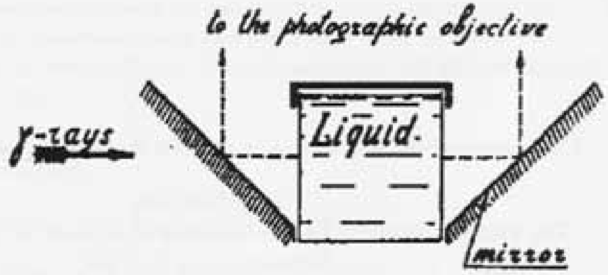

Figure 1: Arrangement of apparatus.

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.

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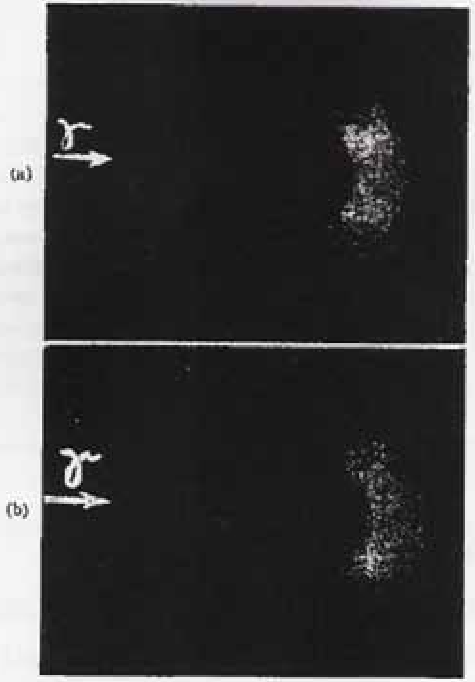


Figure 2: Photographs showing asymmetry of luminescence, (a) water, $n = 1.337$; (b) benzene, $n = 1.513$.

The latter were obtained for ten different liquids. Two of the photographs taken (positive) are represented in Fig. 2. An examination of these photographs leads to the following conclusions:

(1) In all the pure liquids investigated the radiation propagates mainly in the onward direction of the primary beam, the blackening of the negatives being only visible on part of the annular circle.

(2) The area of the blackened sector increases with the refractive index of the liquids (see Fig. 2: (a) $n = 1.337$ for water and (b) $n = 1.513$ for benzene).

(3) Each photograph exhibits two diffuse but clearly visible maxima of blackening, which are symmetrical with respect to the primary beam. Their

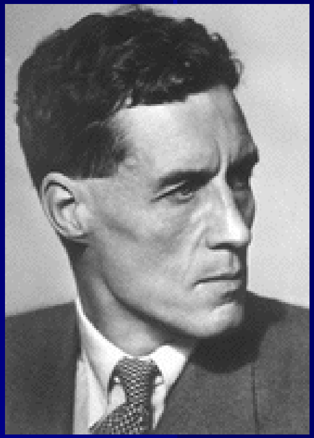
3

Copy of a seminal paper by Cherenkov explaining the essentials of the new emission

Cherenkov light: the beginnings

- It was noticed that the emission is not chaotic, but is related to the track of the moving particle.
- 1946: Vavilov, Cherenkov, Tamm and Frank obtained Stalin‘s prize for their work
- Vavilov is usually given higher credit for the effect
- 1958: Cherenkov, Tamm and Frank obtained Nobel prize
- 1964: Cherenkov became corresponding member of Soviet Academy of Sciences

The Very Beginning of the Atmospheric Air Cherenkov Telescope Technique

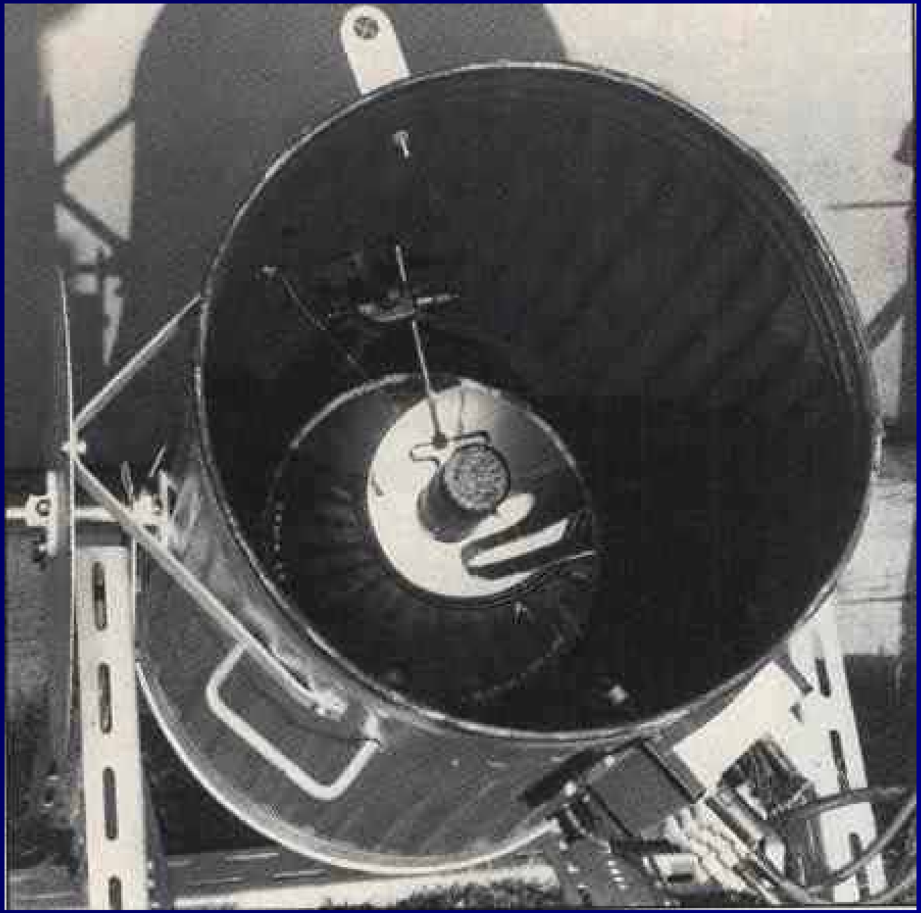


1948

- Blackett (Nobel prize laureate) 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)

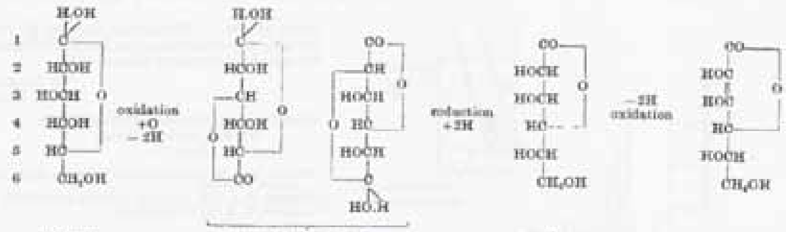
- Until that the Cherenkov light has been detected only in solids and liquids

The Very Beginning of the Air Cherenkov Technique



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.

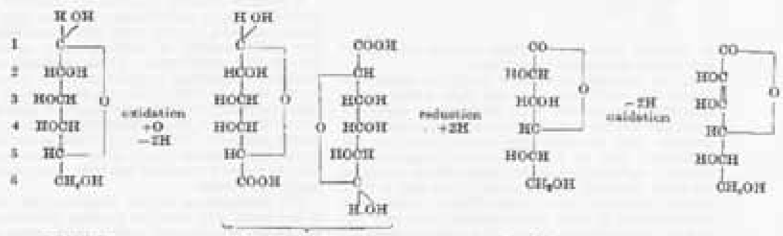


D-glucose

Alternative forms of writing D-glucurono-γ-lactone to show inversion of configuration

L-gulono-γ-lactone

L-ascorbic acid



D-galactose

Alternative forms of writing D-galacturonic acid to show inversion of configuration

L-galactono-γ-lactone

L-ascorbic acid

the animal. There is thus no indication which of our postulated reaction sequences is the more important.

Other mechanisms whereby hexoses might be transformed into L-ascorbic acid, involving L-glyceraldehyde, L-sorbose, D-sorbitol and D-gluconic acid, have not been found in cress seedlings or in the rat.

This work will be published in detail elsewhere.

F. A. Isherwood
Y. T. Chen
L. W. Mapson

Low Temperature Station for
Research in Biochemistry and Biophysics,
University of Cambridge and
Department of Scientific and Industrial Research.
Dec. 6.

[1] Ray, S. N., Biochem. J., 28, 996 (1934).
[2] Jackel, S. S., Mosbach, E. H., Burns, J. J., and King, C. G., J. Biol. Chem., 186, 569 (1950).
[3] Horowitz, H. H., Doerschuk, A. P., and King, C. G., J. Biol. Chem., 199, 193 (1952).

Light Pulses from the Night Sky associated with Cosmic Rays

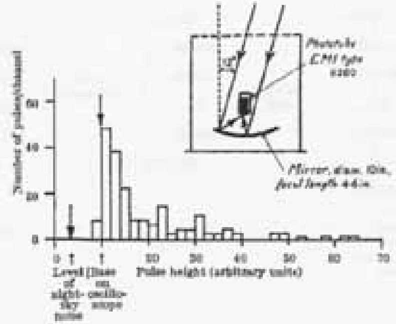
In 1948, Blackett[1] suggested that a contribution approximately 10^{-4} of the mean light of the night-sky might be expected from Čerenkov radiation[2] produced in the atmosphere by the cosmic radiation. The purpose of this communication is to report the results of some preliminary experiments we have 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, inset), the field of view of this 'telescope' being approximately ± 12° from the zenith. The output of the phototube was connected to an amplifier with equal differentiation and integration time-constants of 0·032 μsec. The apparatus was mounted in a field adjacent to this establishment at the centre of a square array of sixteen Geiger–Müller counters (each of area 200 cm.²; the sides of the entire array were 150 metres) designed by Cranshaw[3] for studies of extensive air-showers. The results obtained were as follows.

(a) On the night of September 25–26, the pulses were first observed visually on the oscilloscope and were seen to be several times the mean height of the noise pulses 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, 97 pulses were recorded in 100 min.

Artificial night-sky noise was then produced by means of a small lamp inside a lid placed over the telescope. In 50 min., no noise build-up pulses were observed at the same bias and gain conditions.

(b) Three-fold coincidence pulses corresponding to showers detected by the extensive shower array were used to trigger the time-base of the oscilloscope, and the light pulses (if any) displayed on the Y-plates.



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

(c) 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 Geiger–Müller pulses at the same point on the time-base; two had a coincidence between two Geiger–Müller tubes, one corresponding to three Geiger–Müller tubes and one to four Geiger–Müller tubes. This rate of observing Geiger–Müller pulses on the time-bases associated with light-pulses (when the association is to within 3 μsec.) is approximately a thousand times the accidental coincidence-rate. Moreover, the fact that all the Geiger–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 of gain and bias.

The conclusions are: (i) a large fraction of the light pulses observed are directly correlated with the cosmic radiations; (ii) none of the light pulses may be attributed to spurious effects, for example, high-tension breakdown, electromagnetic pick-up or noise pile-up; (iii) from the steepness of the front of the electrical pulse, it is deduced that the duration of the light pulses is less than approximately 0·2 μsec.

The negative result of experiment (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 Geiger array.

Some of the light pulses observed may result from relatively soft showers high in the atmosphere from which only a few particles survive at sea-level. There is no evidence in the experiments carried out so far to show that the light is, in fact, Čerenkov radiation 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. P. M. S. Blackett, to whom we are grateful for his continued interest. We wish to thank Mr. W. J. Whitehouse and Dr. E. Bretscher for their encouragement, and Dr. T. E. Cranshaw for the use of the extensive shower array.

W. Galbraith
J. V. Jelley

Atomic Energy Research Establishment,
Harwell, Didcot, Berks.
Nov. 19.

[1] Blackett, P. M. S., Physical Society of London Gassiot Committee Report, 34 (1948).
[2] Čerenkov, P. A., C.R. Acad. Sci. U.S.S.R., 8, 451 (1934).
[3] Cranshaw, T. E. (to be published).

Determinations of Size of Particles with the Electron Microscope

A METHOD recently reported by Timbrell[1] for the determination of particle-size with the light microscope has been applied with slight modification to size determinations of textile-bonding agents with the electron microscope. These materials are dispersions of spherical polymer particles having sizes in the range 0–0·2μ. The normal method of size determination involves measurements on photographic plates obtained at known magnification using a transparent graticule. This method, which is tedious, may be subject to errors due to fatigue of the operator; and the method described has been found much more rapid and reliable.

The photographs of the dispersion are obtained in the usual way with the electron microscope, and the plates are trimmed with a glass cutter so that they can be placed in the holder of an ordinary slide projector. The projected beam is intercepted and deviated on to a screen by a front-aluminized glass mirror which can be oscillated about a vertical axis. Size discrimination can then be made as in Timbrell's method, by the number of overlapping areas present on the screen, each representing a particle with a diameter larger than the amplitude of the oscillation. All the determinations made to date with the instrument have been obtained by counting overlapping areas for various settings of the amplitude control, thus giving the cumulative size-distribution curves.

It has been found advantageous to increase the visual effect of an overlap area by introducing a colour contrast in the following way. A circular sheet of 'Perspex' was dyed in two operations so that one half was red and the other half green. This was then

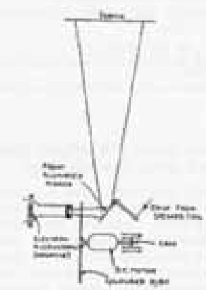


Fig. 1

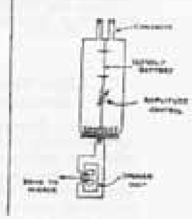
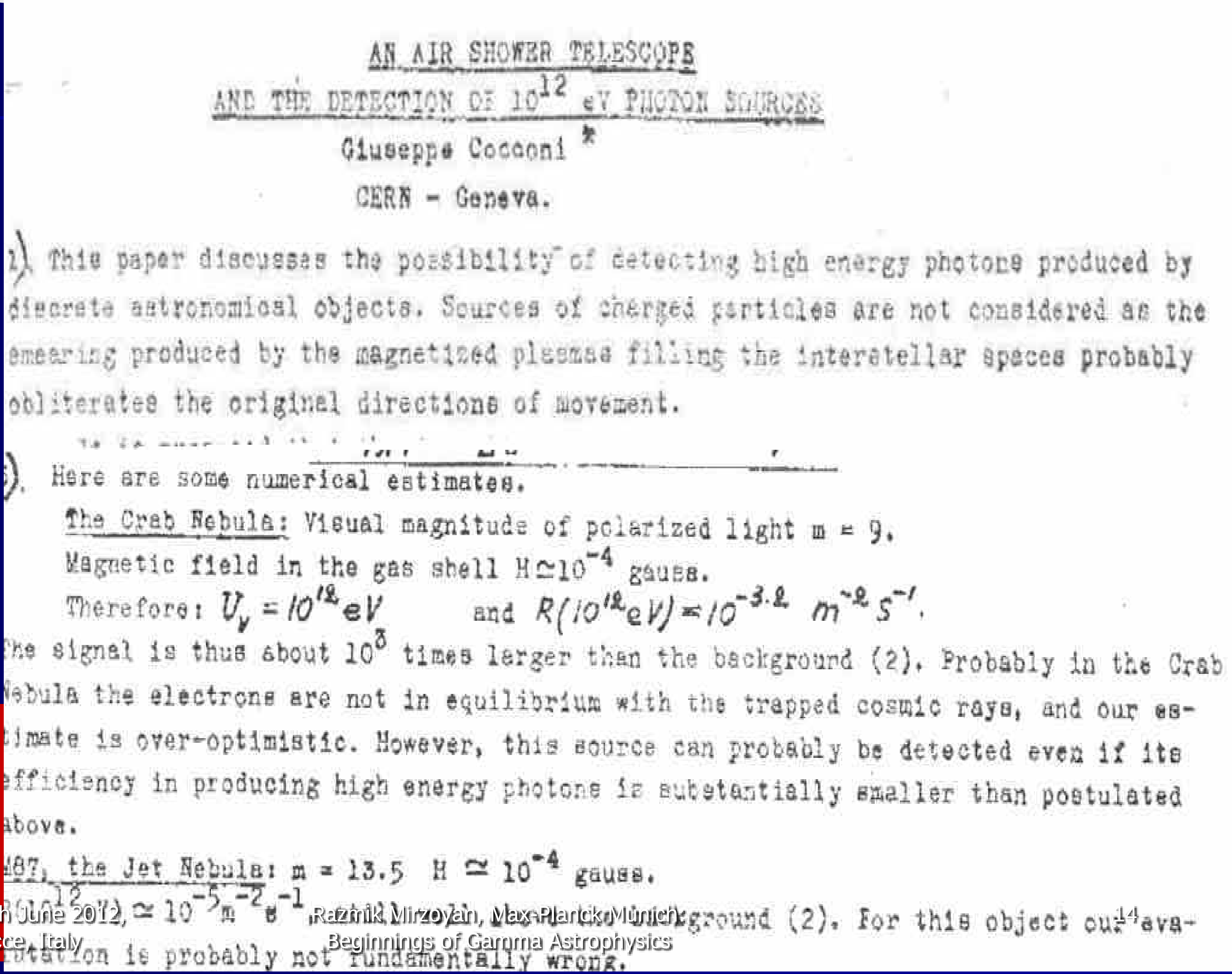


Fig. 2

Gamma-ray Astronomy, the beginning

Seminal paper by Phillip Morrison, 1958



AN AIR SHOWER TELESCOPE

AND THE DETECTION OF 10^{12} eV PHOTON SOURCES

Giuseppe Cocconi *

CERN - Geneva.

1) 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 movement.

5). Here are some numerical estimates.

The Crab Nebula: Visual magnitude of polarized light m = 9.

Magnetic field in the gas shell $H \simeq 10^{-4}$ gauss.

Therefore: $U_\gamma = 10^{12}$ eV and $R(10^{12} eV) \approx 10^{-3.2}\ m^{-2} s^{-1}$.

[T]he signal is thus about 10^3 times larger than the background (2). Probably in the Crab [N]ebula the electrons are not in equilibrium with the trapped cosmic rays, and our es[t]imate is over-optimistic. However, this source can probably be detected even if its [e]fficiency in producing high energy photons is substantially smaller than postulated [a]bove.

[M]87, the Jet Nebula: m = 13.5 $H \simeq 10^{-4}$ gauss.

$R(10^{12} eV) \simeq 10^{-5} m^{-2} s^{-1}$ ... [back]ground (2). For this object our eva[lu]ation is probably not fundamentally wrong.

Also proposed at higher energies independently by Giuseppe Cocconi, 1959

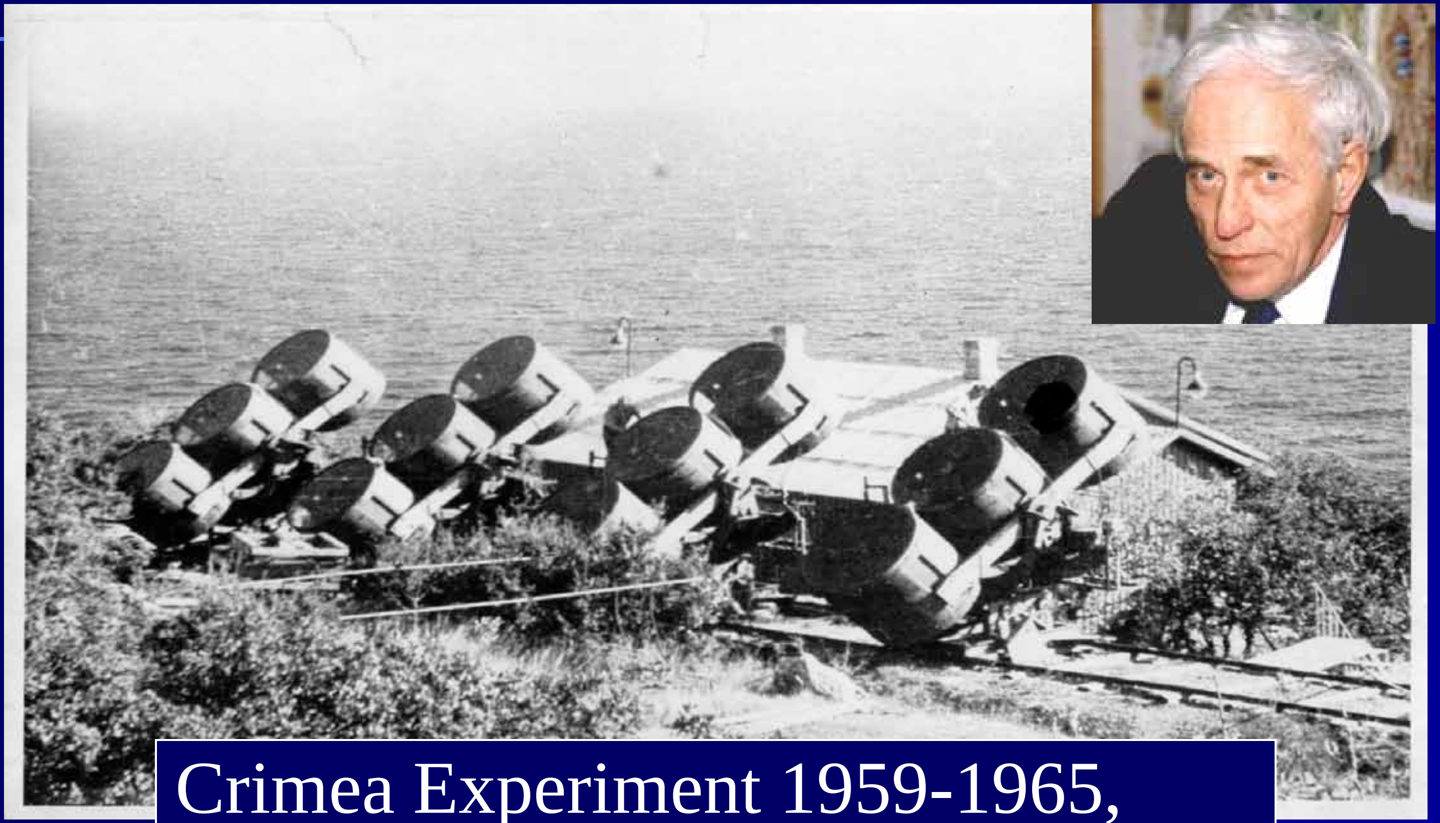
About how could ground-based g astronomy profit from the end of the World War-II

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

- Parabolic search-light mirrors of ~0.5° angular resolution and 1-2 m in diameter

- Gunmounts, also from military ships. Could be used as telescope mounts with readily available drive system

Cherenkov Technique used for Gamma Ray Astronomy



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

Cherenkov Technique used for Gamma Ray Astronomy

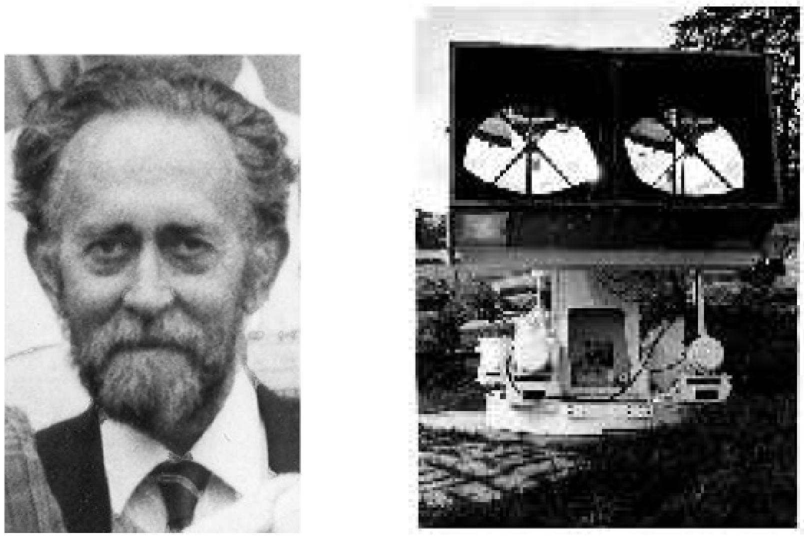


Figure 3. **Left:** Neil A. Porter (1930-2006) (Photo: D.J.Fegan) **Right:** The second ground-based gamma-ray telescope; the British-Irish experiment at Glencullen, Ireland c. 1964; the telescope consisted of two 90 cm searchlight mirrors on a Bofors gun mounting. The experiment was led by Jelley and Porter.

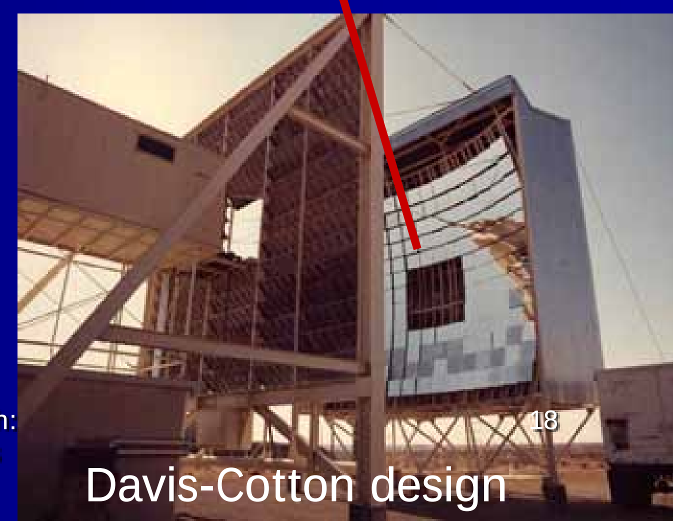
1st Gen. Atmospheric Cherenkov Telescope

Glencullen, Ireland
~1962-66

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

(quasars (AGN), variable stars)

1st Smithsonian venture into VHE gamma-ray used Solar Furnace at Natick, MA ~ 1965-6.
Gamma-ray Astronomy Group led by Giovanni Fazio



First Gamma-ray Experiment at Whipple Observatory, 1967-68

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.

The Pioneer: all life-long trying really hard, again and again, until succeeding in 1988

THE ASTROPHYSICAL JOURNAL, Vol. 154, November 1968

A SEARCH FOR DISCRETE SOURCES OF COSMIC GAMMA RAYS OF ENERGIES NEAR 2×10^{12} eV

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AND

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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 2×10^{12} eV. No statistically significant effects were recorded. Upper limits of $3\text{–}30 \times 10^{-11}$ gamma ray $\text{cm}^{-2}\,\text{sec}^{-1}$ were deduced for the individual sources.

Schmidt Telescope Design with Image Intensifier

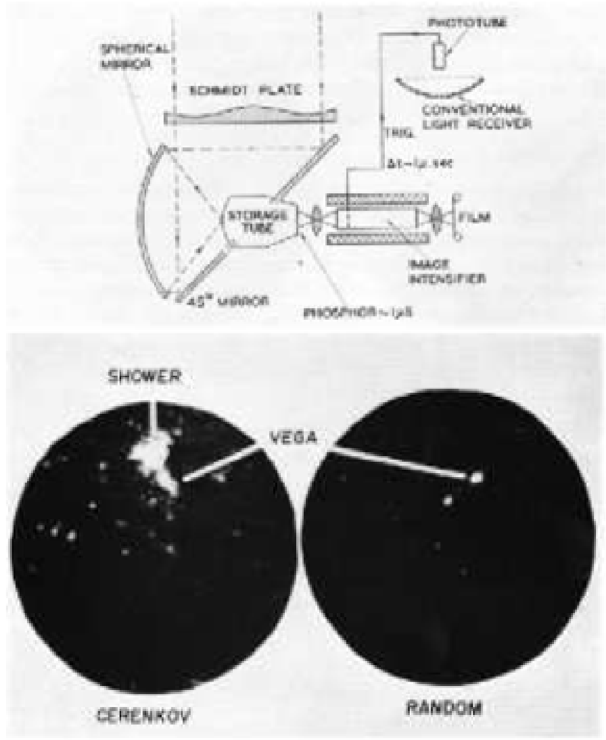


Figure 5. **Top:** Image Intensifier used by Hill and Porter to record the images of cosmic ray air showers [24]. **Bottom** Images of the night-sky triggered by an ACT (left) and triggered randomly (right). The field of view was ±12.5°.

Cherenkov Shower Imaging using Image Intensifiers (1960-65) and Stereo Detectors (1972-76)

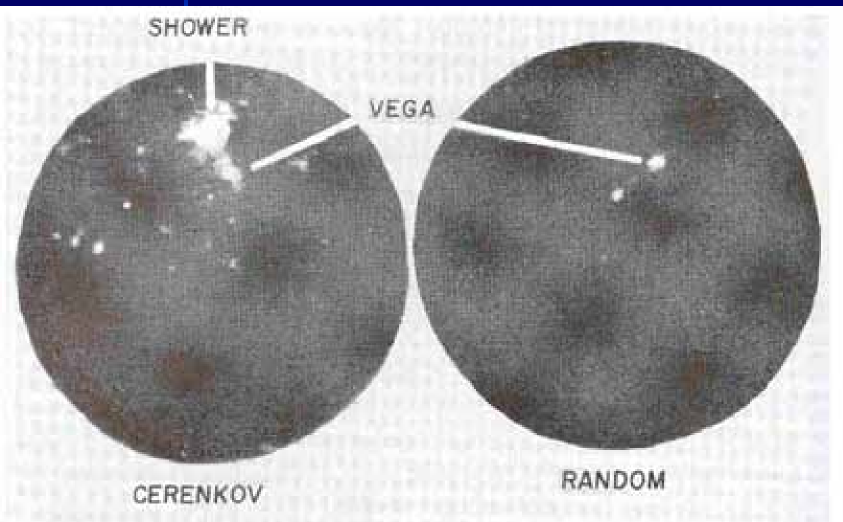
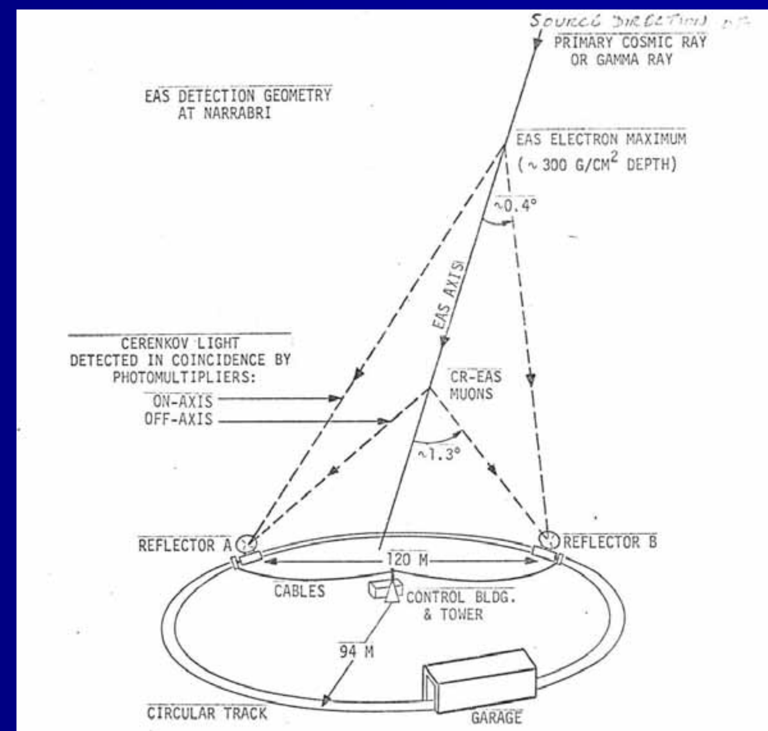


Image Intensifier Pictures of Cherenkov light Image from Cosmic Ray Air Shower.
On short time-scale images are brighter than bright star (Vega).
Work by David Hill (M.I.T.) and Neil Porter (U.C.D.) in 1960



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

The 1st S... on the Potential ... ector

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.

SOVIET PHYSICS JETP VOLUME 20, N

THE ANGULAR DISTRIBUTION OF INTENSITY OF C
EXTENSIVE COSMIC-RAY AIR SHOWERS

V. I. ZATSEPIN

P. N. Lebedev Physics Institute, Academy of Sciences

Submitted to JETP editor March 2, 1964

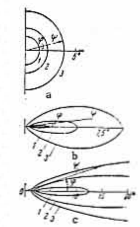
J. Exptl. Theoret. Phys. (U.S.S.R.) 47, 689-696 (Augus

The angular distribution of intensity is calculated for terrestrial atmosphere by extensive air showers of co showers arriving from the zenith and for conditions of titude of 3860 m above sea level. Photographic observ against the celestial sphere, as obtained in [2,3] is evi the calculations.

1. INTRODUCTION

In the registration of extensive air showers (EAS) by means of Cerenkov counters,[1,2] a knowledge of the angular distribution of the Cerenkov radiation is important primarily from the methodological point of view (choice of the angle subtended by the Cerenkov counters to obtain optimal signal-to-noise ratio, estimates of the accuracy of the angular coordinates of high-energy primary particles, and so on). Besides this, the angular distribution of the light from showers is already itself the object of physical investigation,[3] and therefore it is important to ascertain what kind of information about a shower can be obtained from such data. The present calculation has been made for this purpose, and is based on the following ideas.

Cerenkov radiation is mainly caused by the electronic component, which makes up the bulk of the charged particles in a shower. Owing to multiple Coulomb scattering by the nuclei of atoms in the air, electrons of energy E at a depth p have a Gaussian distribution of distances r from the axis of the shower, and a Gaussian distribution of angles relative to a mean angle ϑ, which depends on r. The dispersions of the transverse and angular distributions depend on E. The energy spectrum of the electrons is an equilibrium one and does not depend on the degree of development of the shower in depth. For the case of primary photons the variation of the electrons with height is taken to be that given by the electromagnetic cascade theory,[4] and for the case of primary protons, that given by the calculations of Nikol'skiĭ and Pomanskiĭ.[5] The light emitted by the electrons is at the angle ϑ_{Cer} with the direction of their



ours of equal intensity in the light flash at s from the axis of a shower arising from a ith $E_{ep} = 4.5 \times 10^6$ BeV (3860 m above sea , 2, and 3 correspond to the intensities $^{-1} I_{max}(R)$, and $10^{-3} I_{max}(R)$, and diagrams or distances 0, 100, and 400 m from the er.

10^{15} eV is considerably larger than a shower at sea level. This differ- due to the different distance of the rice from the maximum of the the shape of the spot of light is sen- ight of the maximum of the shower, principle an analysis of the shape so to determine the position of the shower.

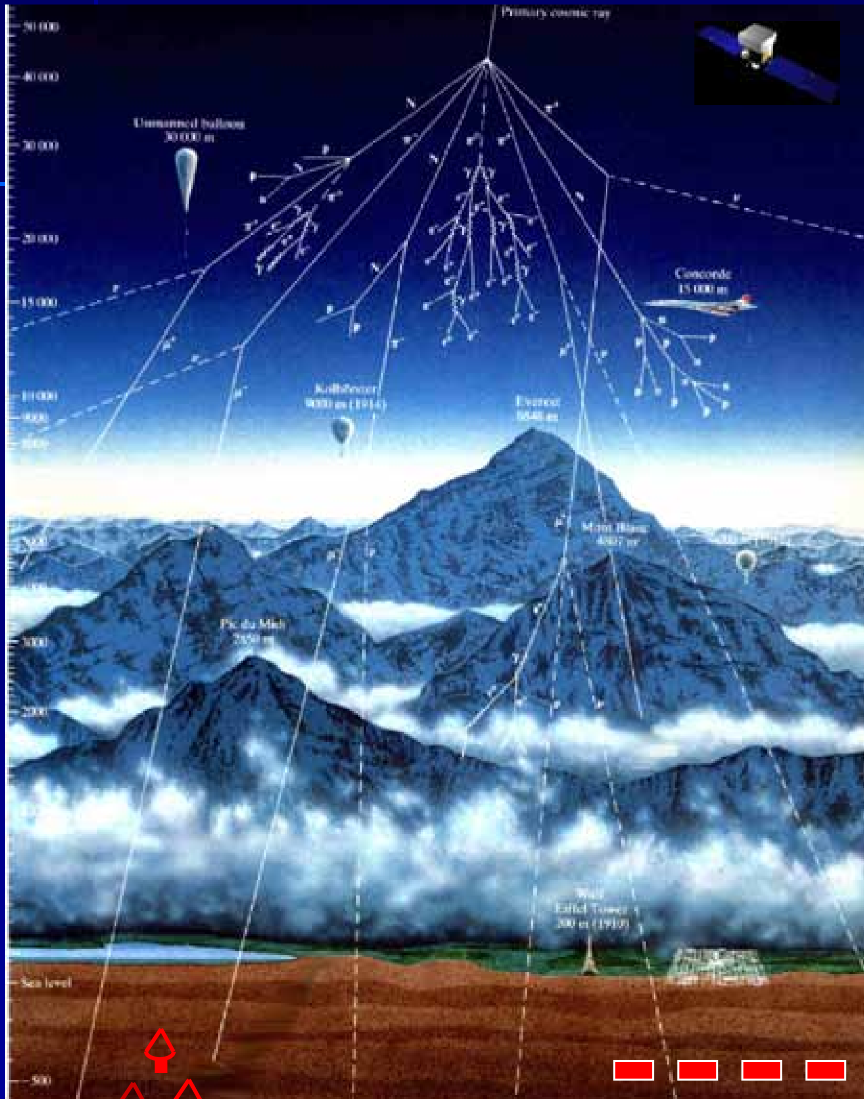
calculations have been made on the ons as the calculations of the spatial the light made in [6], and therefore cked directly by calculating the total ensity

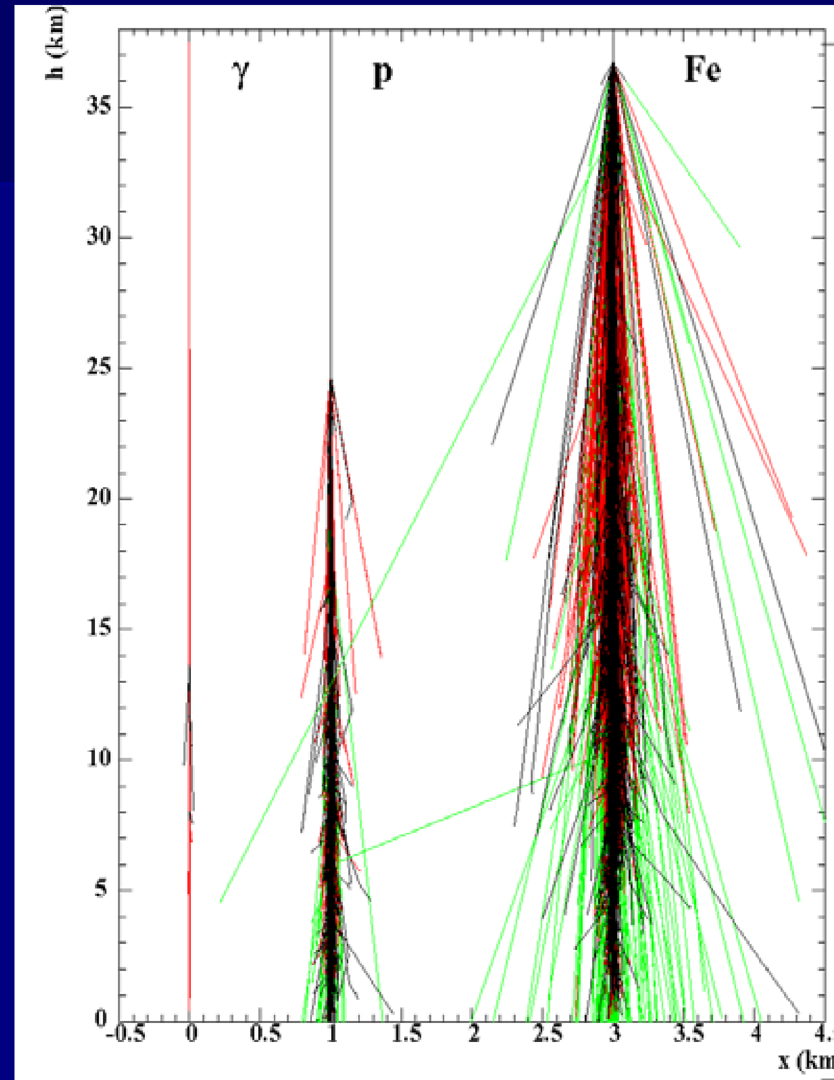
$$\int_0^{2\pi}\int_0^{10^\circ} I(E_0, R, \psi, \varphi) \sin\psi\, d\psi\, d\varphi \quad (11)$$

nce from the axis of the shower and ith the results obtained in [6]. Cal- . (11) have been made for seal level and R = 400 m. The results agreed of [6] to an accuracy of several

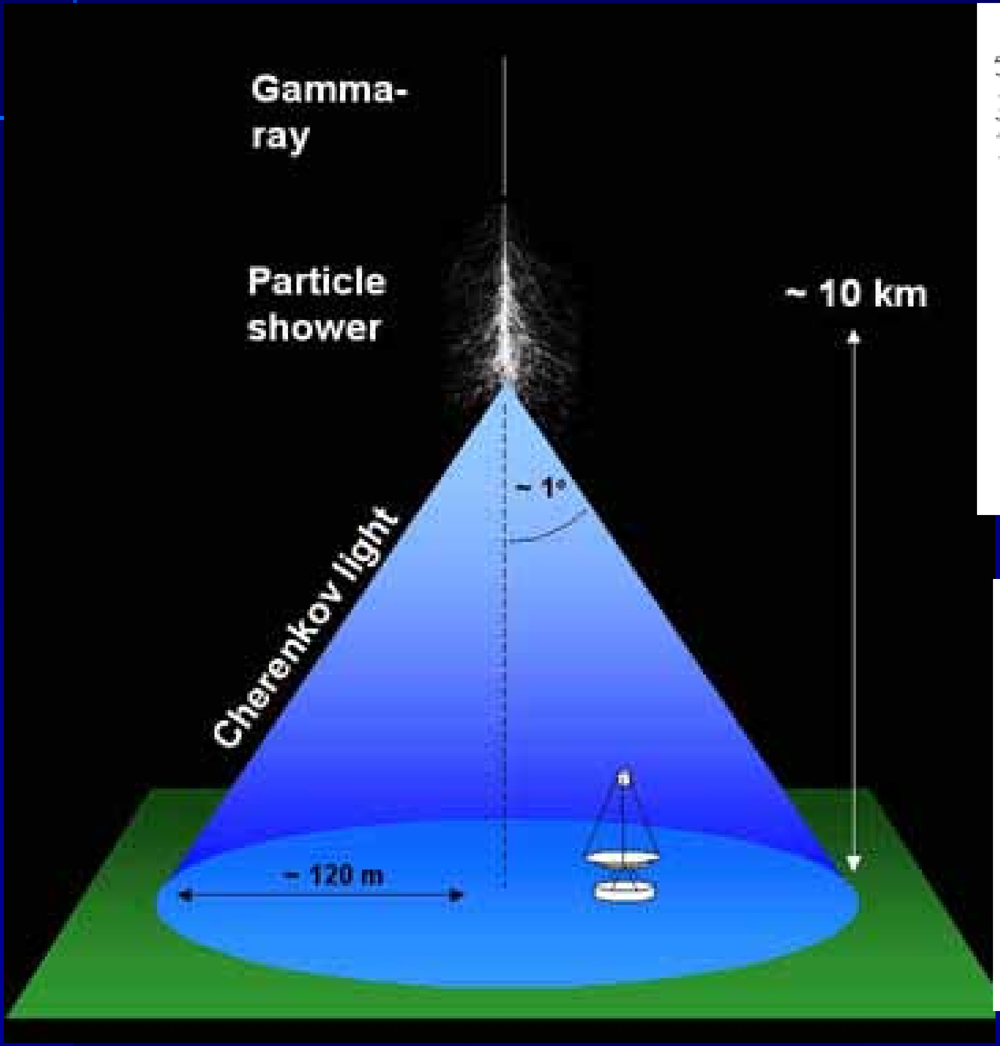
ions that have been made enable us owing conclusions:
maximum intensity of the light from not coincide with the direction of rimary particle, in researches in mination of the angular coordinates particle is made by photographing rom the shower one should seek acy in this determination by photo-

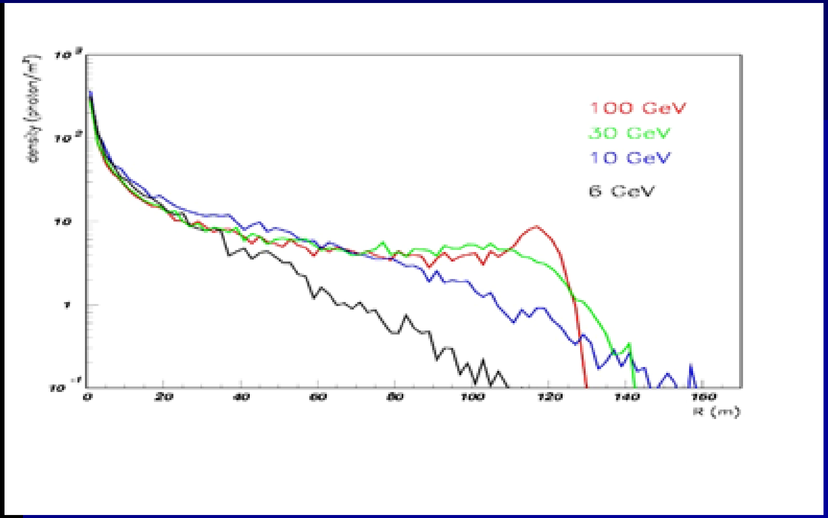
Extensive Air Showers

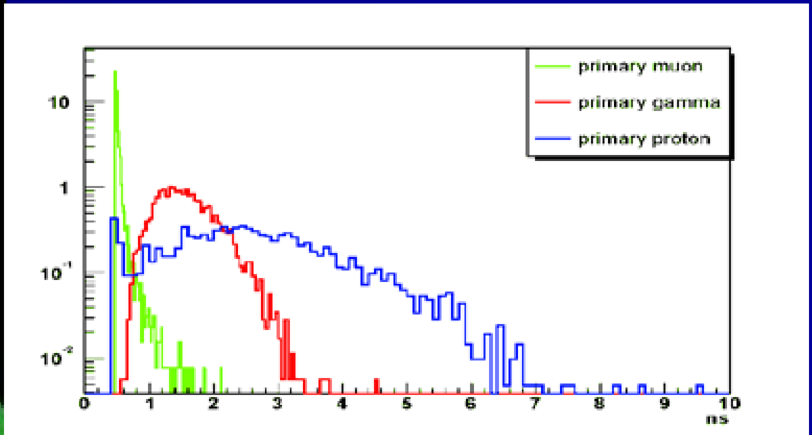


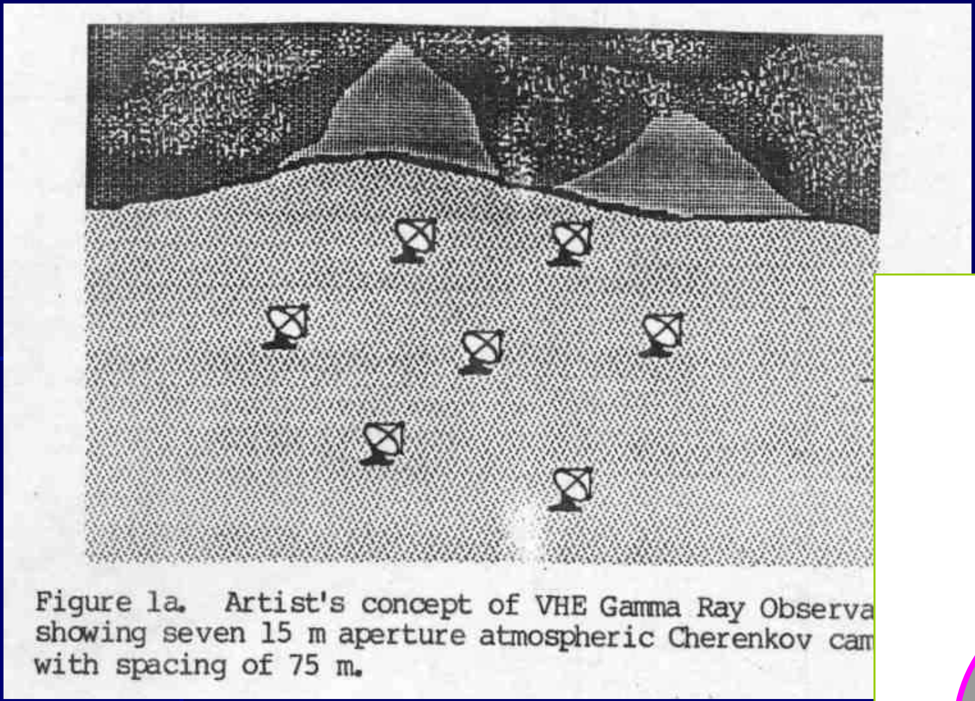


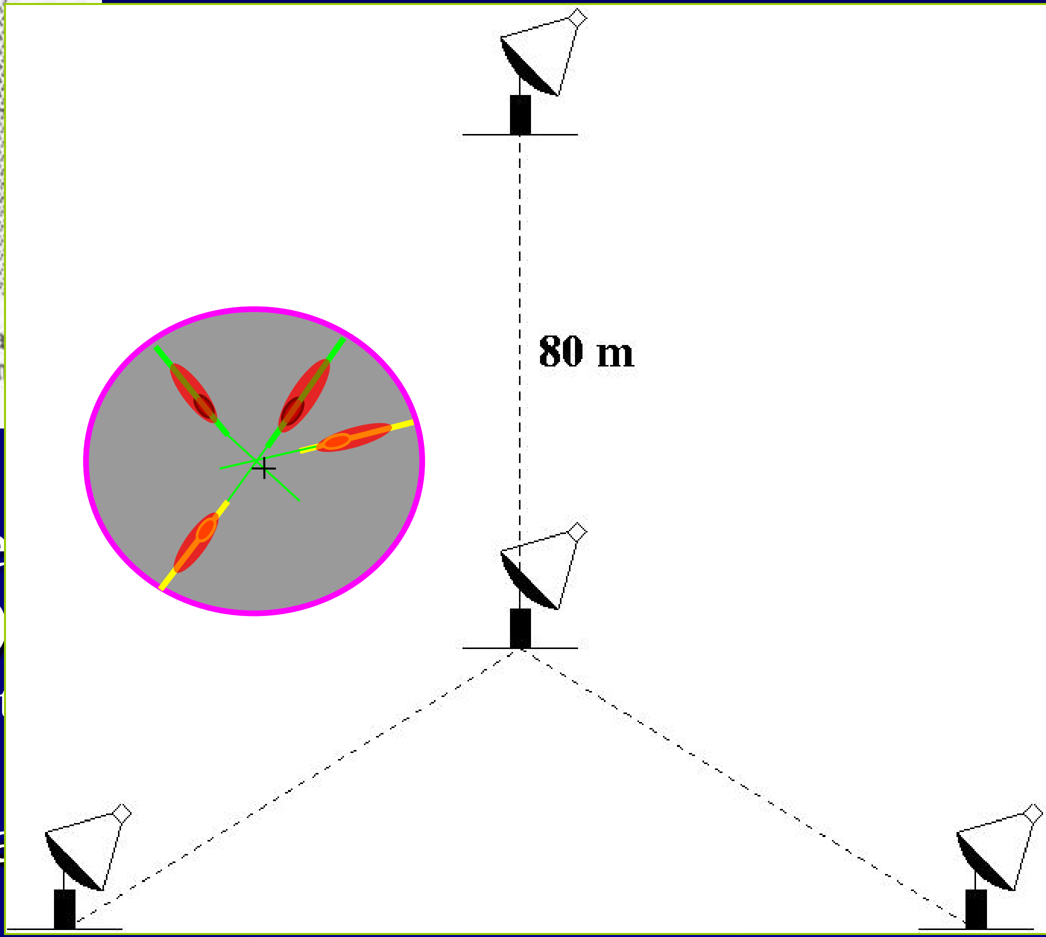
The Cherenkov light pool from a single μ, the time structure of a shower and the light pool of a shower











An array of ACIT's was first proposed in 1984 (prior to the detection of the Crab Nebula)

(NASA Workshop, Space Lab. Science, Bat Rouge, 1984)

This is the configuration that wa later adopted for VERITAS.

Some key developments

- 80‘s: plenty of „discoveries“ on 3-4 s level
- M. Hillas: „A physicist‘s aparatus 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 „a„is a useful parameter
- La Jolla, 1985: Michel Hillas suggested to use the „Hillas“ parameters
- 1989: Whipple discovers 9s signal from Crab

Arnold Stepanian and his 1st imaging "stereo "telescopes: GT-48 in Crimea

20 m distance between the telescopes

VERITAS INAUGURATION, Arizona, April 28th 2007

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“ ;-)

February 1985

Yerevan Physics Institute
Proposal for 5 imaging Cherenkov Telescopes:

90.

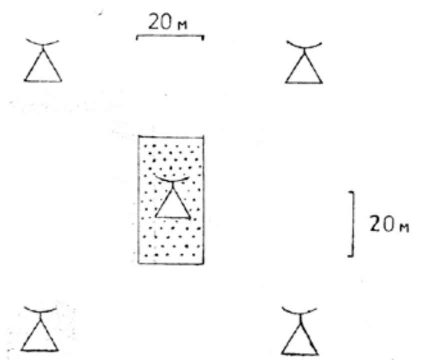


Рис. 38. Установка I,
△ — телескопы для регистрации ЧС ливней с ПЧД.
▣ — детекторы мюонов ШАЛ.

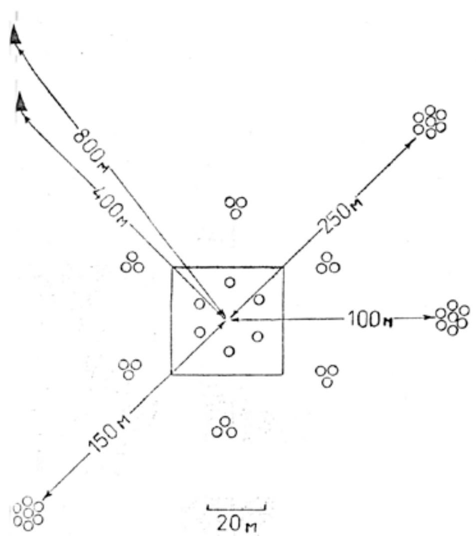


Рис. 39. Установка 2.
□ — центральная часть АНИ для регистрации компонент ШАЛ.
∘; ∞; ⁂ – детекторы для определения поперечного распределения ЧС ШАЛ
▲ — детекторы для определения формы импульсов ЧС ШАЛ.

ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ

А.Т.Авунджян, С.А.Агаджанян, Ф.А.Агаронян, А.Ц.Аматуни,
Г.А.Вартанетян, Э.А.Мамиджанян, С.Г.Матинян, Р.Г.Мирзоян

КОМПЛЕКСНОЕ ИССЛЕДОВАНИЕ ПЕРВИЧНОГО КОСМИЧЕСКОГО ИЗЛУЧЕНИЯ В ОБЛАСТИ ЭНЕРГИЙ $10^{12} - 10^{17}$ эВ"

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

A. A. Stepanian
Crimean Astrophysical Observatory, USSR

D.J. Fegan
University College, Dublin, Ireland

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

ČERENKOV IMAGING TeV GAMMA-RAY TELESCOPE

F.A.Aharonian, A.G.Akhperjanian, A.M.Atoyan, A.S.Beglarian, A.A.Gabrielian, R.S.Kankanian, P.M.Kazarian, R.G.Mirzoyan, A.A.Stepanian*

Yerevan Physics Institute, USSR
*Crimean Astrophysical Observatory, USSR

Abstract

A Čerenkov imaging telescope being under construction for investigation of TeV 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 fluxes 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^{11}–10^{13}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 fluxes at the 9σ level from the Crab Nebula with the Wipple observatory 10-meter imaging Čerenkov γ-ray telescope [2].

In 1989, at the cosmic ray station of Yerevan Physics Institute, near the Byurakan optical observatory (40.18° N latitude and 44.5° 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 main 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 reflector of the telescope consists of 19 separate 60-cm round glass mirrors with a total collection area of 5.3 m^2. 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, 610mm 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-time 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 ≤20 seconds of arc. Such a high quality of mirrors is very important, especially for further improvement of the

36

The 1st telescope (of 5 planned) I´ve built: 1989

Nor Amberd cosmic ray Station, mount Aragats, 2000 m a.s.l., Armenia

31. 5. 91

Proposal
for
Imaging Air Cherenkov Telescopes in the
HEGRA Particle Array

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R.G. Mirzoyan, A.A. Stepanian*

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* Crimean Astrophysical Observatory

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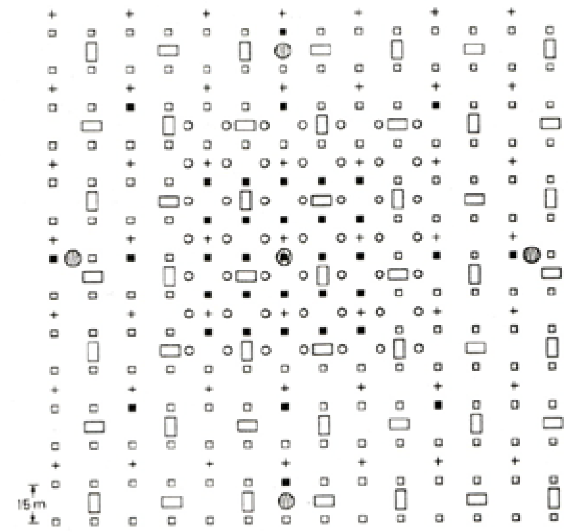

ELECTRON DETECTORS: 1 m^2 scintillation counters for particle density and fast-timing measurements (2 PM's each), with 5 mm of lead for photon conversion.

- ■ 37 detectors in operation since July 1988 (University of Kiel)
- □ 159 additional detectors, 90 of them in operation since July 1989, the rest since December 1990 (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 m^2 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 wit h 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.

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.

The 1st telescope of HEGRA, the CT1 (installed spring 1992)

THE SYSTEM OF IMAGING ATMOSPHERIC CHERENKOV TELESCOPES: THE NEW PROSPECTS FOR VHE GAMMA RAY ASTRONOMY.

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(Received 7 April 1992; accepted 15 October 1992)

Using Monte Carlo simulations the possibilities are investigated for registration of VHE gamma radiation by means of systems of imaging air Cherenkov telescopes (IACT). It is shown that even a system of IACT's with moderate properties (three telescopes with the geometrical area of the optical reflector $\simeq 5\ m^2$ and the angular size of the pixel $\simeq 0.41^0$) could provide the energy resolution 20–25% and achieve the sensitivity (minimum detectable flux) up to $10^{-12} photon/cm^2 s$ at the effective energy threshold $\simeq 1$ TeV.

1. Introduction.

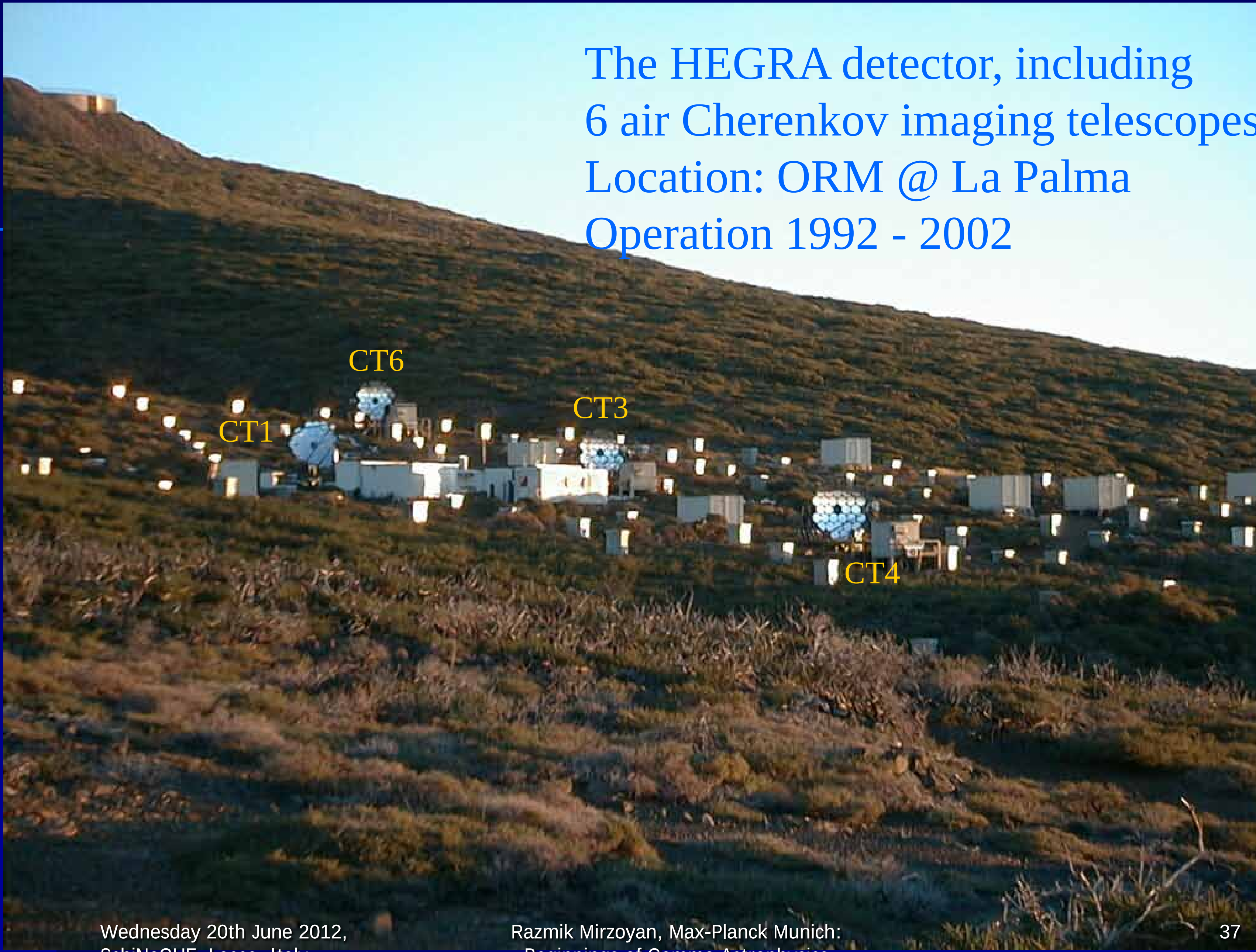
So far all observations of primary gamma rays at E≃1 TeV have been made with Air Cherenkov Telescopes (ACT). In the foreseeable future this technique will dominate at least at energies E≤10 TeV.

One of the most remarkable features of the ACT's is their high rate capability. For collection area $S_{eff} \geq 3 \cdot 10^8 cm^2$, 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

Experimental Astronomy 2: 331–344, 1993.

Results of our 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), nevertheless we understood the strong background rejection feature of the multiple telescopes.

The HEGRA detector, including
6 air Cherenkov imaging telescopes
Location: ORM @ La Palma
Operation 1992 - 2002

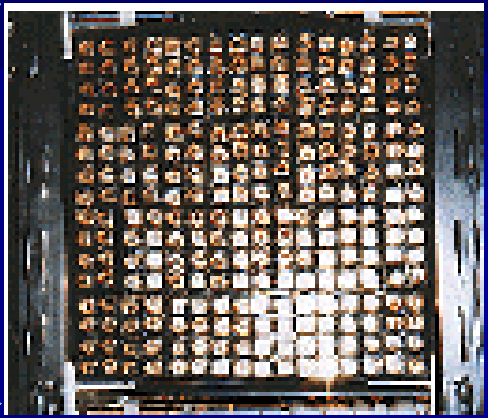


Sources seen by the HEGRA telescopes. Flux is in Crab units.

H: HEGRA; C: CAT; W: Whipple; T: 7-Tel. Array

Source	Type	Distance kpc or z	S_{HEGRA}	Flux (in Crabs)	Experim.
Crab Nebula	Plerion	1.6 kpc	>> 10	1.0	Many
Cas A	SNR (shell)	3.4 kpc	~ 6	0.03	HEGRA
TeVJ2032+41	Unknown	Unknown	~ 7	0.03	HEGRA
Mkn 421	BL Lac	0.030	>> 10	0.04 - 8	Many
Mkn 501	BL Lac	0.034	>> 10	0.33 – 11	Many
1ES 1959+650	BL Lac	0.047	>> 10	0.05 – 2.2	H, W, C, T
H1426	BL Lac	0.129	~ 7	0.03 – 0.08	H, W, C
1ES 2344+514	BL Lac	0.044	~ 4	0.03	H, W
M87	Radio gal.	0.0044	~ 4	0.03	H

The 1st Cangaroo telescope in Australia



Kifune, et al.,

The 3.8m telescope on a alt-azimuth mount was an ex-lunar-ranging telescope used in Dodaira observatory of the National Astronomical Observatory of Japan

Japanese 7-telescope Array in Utah, USA

Teshima, et al.,

But ...
gamma-ray astronomy is a risky business…

Cruise Missile Mishap
10. Dec.'97

Beginning of MAGIC

- A $10m^2$ telescope has a threshold of ~1TeV
- Since from the beginning it was a common belief that threshold of a Cherenkov telescope

$$E_{thr} \sim \sqrt{(1/A_{mirror})}$$

- That was suggesting that one needs a $A_{mirror} \sim 10^4 m^2$ for measuring few 10's of GeV; à 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

$$E_{thr} \sim 1/A_{mirror}$$

Beginning of MAGIC

- After that started looking for a telescope with $A_{mirror} \geq 200\ m^2$. 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_{thr}~40 GeV

- It became clear: there was a very strong background at several tens of GeV à Multiple telescopes were needed.

VERITAS, H.E.S.S. & MAGIC: the triumphal procession of VHE g-astro-physics is continueing

Outlook : the next 5-7 years

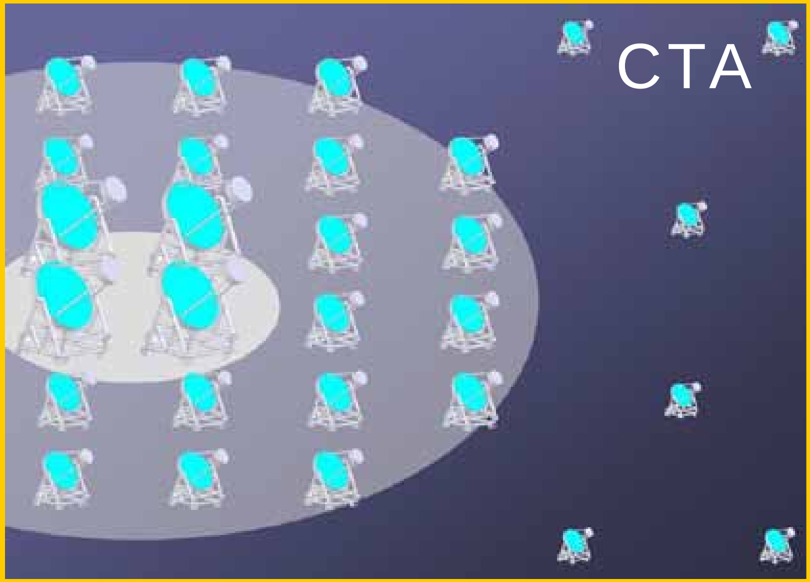
Next generation VHE gray Observatory: CTA

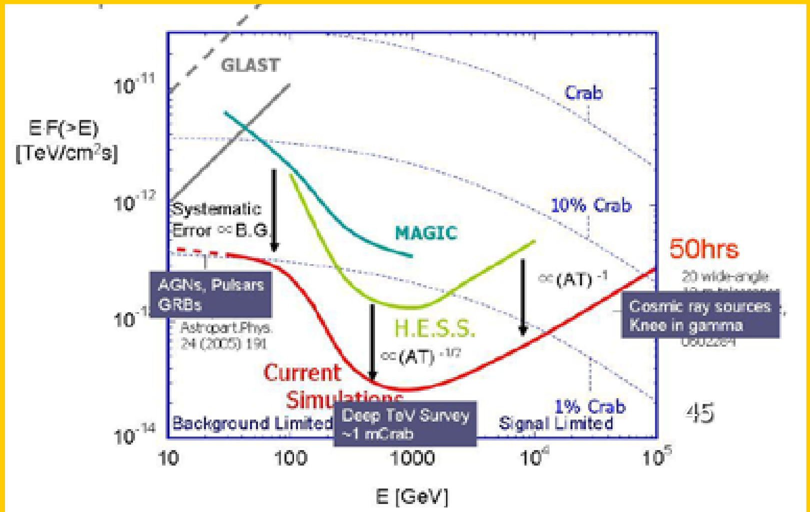
MAGIC Phase II (MAGIC-I + MAGIC-II) since 2009
~150 sources are already discovered

HESS Phase II (HESS + 28m Telescope) in 2012

~1000 scientists
~120 institutions

Cherenkov Telescope Array
1000's of sources will be discovered





Astronomers in EU

JAPAN, US