STEADY, PERIODICAL OR EPISODIC EMISSION - WHAT IS MORE PROMISING IN THE CASE OF UHE GAMMA-RAY ASTRONOMY ?*

1. Introduction

The ground-based gamma-ray astronomy at very high and ultrahigh energies is now 32 years old. Many exciting discoveries had been announced during this long period both in the VHE and UHE range, but the general result is rather pessimistic. Only one positive evidence looks now as fully convincing - the steady emission from the Crab at ~ 1 *TeV*, as measured by the Whipple Observatory group.

This important success was achieved not by accumulating more and more data, but due to improvement of air Cherenkov technique using the imaging system method which made it possible to reduce the cosmic ray background by more than an order of magnitude. At the same time the Whipple data, based on the imaging technique, discredited some positive evidence of such favourite sources as Hercules X-1 as well as periodical signal from the Crab itself.

One should have in mind that, though already 4 years passed after the announcement of the first significant Whipple result, their data on Crab remains unique, still not repeated and confirmed by another group[1]. I believe the developing of the successful imaging technique and further observation of Crab to be very important. The comparison of time structures of 1 *GeV* and 1 TeV gamma rays from the Crab shows that the areas of their production and, probably, the generation mechanisms are quite different. While $0.1 \div 1$ *GeV* signal can be produced by inverse Compton effect near the pulsar itself, the *TeV* signal looks as produced in the Nebula, the process being rather $pp \to \pi^0 \to 2\gamma$. The presence or absence of the pulsed component from Crab at 1 *TeV* becomes quite crucial.

The main difficulty in planning the experimental search of gamma ray sources by ground-based installations is the absence of reliable theoretical prediction of fluxes, energy spectra and time structure, especially in the UHE range. The situation now is quite different as compared to the motivation of our work at Katsively 32 years ago.

At that time there was quite definite prediction of *TeV* gammas from sources, emitting synchrotron radiation in visible light range. The prediction was based on the assumption, that *TeV* electrons responsible for this radiation, had been produced in the process $pp \to \pi^{\pm} \to \mu^{\pm} \to e^{\pm}$. Then the $pp \to \pi^0 \to 2\gamma$ process should produce gammas

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[1] At this Conference two important developments arrived: 1) the confirmation of the Whipple result on Crab using a different air Cherenkov technique (fast timing long base multi-mirror systems Asgat and Themistocle), and 2) observation of Mrk 421 by Whipple telescope itself. The last one is the most exciting expanding the area of research to distant extragalactic object, which is impossible for UHE range due to microwave background absorption.

with the same energy as mentioned electrons and their energy flux should be equal to the synchrotron energy flux.

At the 6th ICRC held in Moscow in 1959 G. Cocconi suggested to verify this idea using a conventional EAS array of scintillators at mountain altitude. But the proposed parameters of array as ~ 1 *TeV* energy and angular resolution occurred scarcely to be obtained, so G.T. Zatsepin suggested to use air-Cherenkov technique.

We built the first version of air shower Cherenkov telescope at Katsively (Crimea) and got the first results in 1960. Then we spent the other three years improving the technique and accumulating the data on different potential sources [1]. Many millions of showers have been recorded in the "drift scanning" mode. No signal from any source has been seen. The typical upper limit for the explored sources was $\sim 5 \cdot 10^{-11}\ cm^{-2}\ sec^{-1}$. For the Crab it is two orders of magnitude less than the above mentioned prediction. So the hypothesis concerning the secondary origin of *TeV* electrons in the Crab occurred to be wrong. The prevailing part of these electrons should be permanently directly accelerated in the source.

We stopped our search in 1963 because of the absence of the theoretical or experimental encouragement and because of specific difficulties due to systematic errors, when the signal to background ratio becomes less than one per cent, making simple increase of statistics not promising.

For more than 20 years I wondered whether the decision to stop Katsively experiment was right or wrong ? Many discoveries were made but no one fully convincing. At the Workshop on Very High Energy Gamma Ray Astronomy in Ootacamund, India in 1982 [2] the question was mentioned: why in Katsively experiment with more than 20 m^2 area of parabolic mirrors no signal had been seen, while later with less powerful instrumentation the authors obtained the positive evidence? One of possible explanations could be the development of the search for periodical structure in the signal and correspondingly the use of tracking mode instead of drift scan mode. Certainly after the discovery of pulsars and binary sources great attention should be paid to possible periodicity. If observed it could be decisive in identifying the source and, probably, specifying the mechanism of gamma ray production. But I can not agree that the search for periodically modulated signal is more sensitive than the search for a signal from an assumed direction in integrated form, or so called D. C. mode. I have already mentioned this problem in my lecture at Erice in 1988 [3], and would like to discuss it here in more detail. The problem certainly concerns not only VHE, but UHE range as well.

2. Comparison of the search for periodical and steady emission

Let us suggest that during the observational time t the expected number of counts from the point-like source is $\overline{M}$ and the expected (known) background is $\overline{N}$. Certainly $\overline{M} \ll \overline{N}$ and their ratio depends on the angular resolution of the instrument. Suppose that the signal from the source has a periodical structure with a *known* period T and a simple light curve with the emission concentrated uniformly in one interval of phases $\phi_2 - \phi_1 = \Delta\phi$.

To establish the existence of the source we shall try the search for nonuniformity of the phase diagram with a period T for $N + M$ signal (search for periodicity) and compare it with the search of the excess $N + M - \overline{N}$ (D. C. mode). The question can be formulated like this: what method is more convincing or what method needs less time to obtain a given confidence level ?

For the search of periodicity we shall try two most popular methods: the Rayleigh test and the histogram test. In the latter case we shall use the famous χ^2 or Pearson test.

2.1 *Rayleigh test*

Let us denote as ϕ_i $(0< \phi_i < 1)$ the phase of arrival time of each of the $N + M$ recorded events. Then the value of z^2

$$z^2 = \frac{2}{N+M}\left[\left(\sum_{i=1}^{N+M} Cos 2\pi\phi_i\right)^2 + \left(\sum_{i=1}^{N+M} Sin 2\pi\phi_i\right)^2\right] \qquad (1)$$

can be used as a measure of the amplitude of the first harmonic. For uniform distribution the probability to observe this value bigger than certain z is:

$$P_R(>z) = \exp\left(-\frac{z^2}{2}\right) \qquad (2)$$

For the shape of a light curve with the active phase interval $\Delta\phi$ the mean expected value of z^2 $(N < M^2 << N^2)$ is

$$\rangle z^2 \langle = \frac{\overline{M}^2}{\overline{N}+\overline{M}} \cdot \frac{1 - Cos 2\pi\Delta\phi}{\pi^2(\Delta\phi)^2} + 2 \qquad (3)$$

Using equations (3) and (2) for a given $\overline{N}$, $\overline{M}$ and $\Delta\phi$ we can find z and $P(>z)$ and then compare $P(>z)$ with the probability to observe the given excess M in a null hypothesis for a D.C. mode:

in Gaussian approximation $$P_G(\geq M) = \frac{1}{\sqrt{2\pi}} \int_{M/\sqrt{N}}^{\infty} e^{-x^2/2} dx \qquad (4)$$

in Poissonian approximation $$P(\geq M) = e^{-N} \sum_{k=\overline{N}+\overline{M}}^{\infty} \frac{\overline{N}^k}{k!} \qquad (5)$$

2.2 χ^2*-test*

Suppose that our $N + M$ counts are arranged in a form of histogram (phasogram) consisting of n equal bins. As a measure of nonuniformity of the phasogram let us take

$$\chi^2 = n\sum_{i=1}^{n}\frac{\left(x_i - \frac{N+M}{n}\right)^2}{N+M} \qquad (6)$$

which actually is distributed as χ^2 with n-1 degrees of freedom, but this small difference from usual n degrees is of no importance practically when n is about 10 and more.

For the same assumption as before the mean value of χ^2 is:

$$\chi^2 \approx n + \left(\frac{1}{\Delta\phi} - 1\right)\frac{M^2}{N+M} \qquad (7)$$

Practically in our case the χ^2 or Pearson test coincides with the determination of the observed dispersion and comparison of it with the expected one. But to estimate the probability of a large deviation of observed dispersion from the expected one in a null hypothesis it is better to use the χ^2 distribution. To calculate these probabilities we use a simple formula valid for even n :

$$P(>\chi^2) = \exp\left(-\frac{\chi^2}{2}\right)\sum_{k=0}^{\frac{n}{2}-1}\left(-\frac{\chi^2}{2}\right)^k \frac{1}{k!} \qquad (8)$$

Now let us select some confidence level expressed, say, in the "number of sigmas" μ for a Gaussian distribution. Assuming $M << N$ and $M >> 1$ the value of μ is $\mu = M/\sqrt{N}$.

To compare the efficiencies of different methods of search for a point-like source let us calculate the ratio of times one needs to accumulate necessary statistics for a given confidence level. Taking P_G ($>\mu$) as in (4), Rayleigh probability from (2) and (3) we obtain

$$\frac{T_{DC}}{T_R} = \frac{\mu^2(1 - Cos\,2\pi\Delta\varphi)}{2\pi^2(\Delta\varphi)^2[-\ln P_G(>\mu) - 1]} \qquad (9)$$

where T_{DC} is the time, necessary to get " μ sigmas" in DC mode (the background being known), and T_R is the time to get the same confidence level with the Rayleigh test. The similar ratios for DC and histogram (or χ^2) test using (4), (7), (8) are

$$\left.\begin{aligned}\frac{T_{DC}}{T_{\chi^2,n}} &= \frac{\mu^2}{\chi_n^2 - n}\left(\frac{1}{\Delta\varphi} - 1\right) \qquad for \quad \Delta\varphi > \frac{1}{n} \\ \frac{T_{DC}}{T_{\chi^2,n}} &= \frac{\mu^2}{\chi_n^2 - n}(n-1) \qquad for \quad \Delta\varphi < \frac{1}{n}\end{aligned}\right\} \qquad (10)$$

Here $\chi^2(n, \mu)$ is found by interpolation method from (8) so that $P_G(\mu) = P_{\chi^2,n}(\chi^2)$. The result for $\mu = 3$ ($P_G = 1.3 \cdot 10^{-3}$) is shown in the fig. 1.

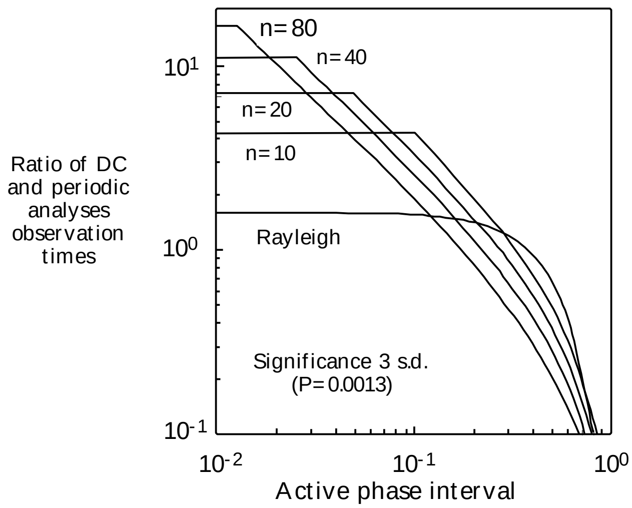

Fig. 1 Comparison of the efficiencies of the search for periodic emission or steady (DC) emission

If one chooses stronger significance, say $\mu = 5$ ($P_G = 2.7\ 10^{-7}$) then the curves should be shifted a little bit higher: by 10 % for the Rayleigh test, and for the histogram test by 31, 39, 45, 50 % , when n is equal to 10, 20, 40, 80 respectively.

One can see from fig. 1 , that for $\Delta\phi \geq 0.5$ the Rayleigh and all histogram tests are less efficient than the DC mode. For very small $\Delta\phi$ the Rayleigh test gives a gain only of 1.6. One can expect the gain an order of magnitude when $\Delta\phi$ is about 1 % or less but this seems to be nonpractical if there is no strong theoretical indication for such an extremely short pulse.

Remember, that if this assumed pulse contains, say, only 30 % of the total emission - the gain will completely disappear. One can say that in a VHE range, using air Cherenkov technique in a tracking mode, the additional time should be spent measuring the background, and because of this T_{DC} should increase by a factor of 4. That means that the search of periodicity is more favourable in the VHE range than in UHE range. But my opinion is that this privilege is not enough to change the general conclusion: in the case, when the fact of periodicity with shape of the light curve is not strictly predicted theoretically, the search for the signal in a D.C. mode should be much preferred. This conclusion certainly becomes much stronger if the period itself is unknown, or is to be adjusted in the analysis of the data.

3. The steady emission

This, I believe, is the most promising approach. But the success is expected mostly by reducing the background, not so much by accumulating more and more statistics. The Whipple result well confirms this my opinion. If the observed signal corresponds to ON/OFF ratio of about 1.01, and the statistical error is much less as should be, the assurance of the absence of systematic errors becomes a problem. We faced it in our old Katsively experiment and at that time elated the effect to the stars happening to occur in the field of view of the telescopes. Now in Baksan experiment in UHE range using a counter technique we are free of the influence of stars, but again there is a lot of difficulties in the analysis of effects of the order of 1 %. Part of them we have found to be connected with some nonstability in timing system, which produces a small distortion in the angular resolution. This makes the result sensitive to the tiny details of the algorithm of angular reconstruction. At Baksan we had a biggest DC-effect ($\sim 3\sigma$) in 1986 for Cyg X-3 and Her X-1 . After reanalysis of these data, using as we believe a better algorithm, the positive effect for Cyg X-3 completely disappeared and for Her X-1 became $\sim 1\sigma$. The total data accumulated for many years are compatible with zero signals from these particular objects. I believe that the future of UHE gamma-ray astronomy is in reducing of the cosmic ray background both by installing huge muon detectors and by improving the angular resolution.

4. Episodic (burst-like) emission

The duration of such bursts observed and announced so far varies from several minutes to several days. The number of events recorded in the angular window directed to the presumable source varies from tens to hundreds. Again there is no definite theoretical prediction that some astrophysical objects should behave in such a way producing bursts of VHE and UHE gammas. But purely experimental advantages of observation of this phenomenon are obvious. From the figures mentioned above any significant, e. g., $\geq 3\sigma$, effect should correspond to the increase of several tens of per cents. The tiny drift of sensitivity or deformation of angular window usually do not contribute to the excess of $\geq 10\%$. One cannot, however, exclude some exotic, nonfamiliar noise or similar phenomena. So for this type of recording the crucial thing is the simultaneous observation of the burst by several independent installations. Unfortunately, most of observations are single ones. Among them very remarkable is the event recorded at Pachmarhi [5] from Her X-1 in *TeV* energy range. The duration of the burst was 14 *min*, significance $\sim 42\sigma$. No simultaneous observation has been made by any other Cherenkov telescope.

At Baksan we have observed similar burst for Cyg X-3 on July 25, 1989 at 23 *h* UT but with an EAS array and in UHE range. The duration of the burst is one hour and significance equals to 3.4 σ (only). This could be increased up to 5σ by optimization of the angular window. But in this case there was another instrument in operation: EAS-TOP in Gran Sasso, Italy. At the moment of the "burst" Cyg X-3 was there in a better position, just in culmination, and there was no positive effect at all. This was a lucky case when there happened to be a proof that the Baksan event 25 July, 1989 had the instrumental origin or was a rare statistical fluctuation.

There was another burst from Cyg X-3 recorded at Baksan 14, 15, and 16 October, 1985, that happened one week after the powerful radio outburst [6]. But at that time Baksan EAS array was the only one looking for point-like sources in 100 *TeV* energy range, and no verification could be made.

Another very exciting event had been recorded by the CYGNUS array at Los Alamos from Her X-1 on July 24, 1986 [7]. The event consisted of two "bursts" with durations 30 and 15 *min* containing 7 and 10 showers. The search for periodicity showed some period, but not exactly the same as well established X-ray period, but very near to recorded twice by air-Cherenkov telescopes in the VHE range. Unfortunately, in this case again no independent confirmation by simultaneous recording is available.

It seems that the event from Crab on Feb 23, 1989 is the only case of "multiple" recording of "episodic" or "burst-like" emission. This time the increase had a duration more than 4 hours, but not much more. It was seen by KGF EAS array in India, by Baksan and Tien Shan arrays in the USSR, and by EAS-TOP array in Italy, but was not seen by HEGRA at Canary Islands and by Akeno in Japan. All four EAS arrays indicating the excess from the Crab on particular day Feb 23, 1989 had the statistics not enough to look for any change of the signal during the visibility of the source (~ 4 hours).

Table 1.

Array	Observation time (range of UT)	Counts ON	Counts OFF	Excess (s. d.)	Probability
KGF [8]	13-16	35	17.8	4.1	$3.4 \cdot 10^{-4}$
Tien Shan	13-16	6	1.6	3.5	$6 \cdot 10^{-3}$
Baksan	15-18	55	34.1	3.6	$6 \cdot 10^{-4}$
EAS TOP (Gran Sasso)	17-20	38 403	25.5 378.3	2.3 1.2	$1.7 \cdot 10^{-2}$ 0.12

The Table 1 represents the data obtained by four different installations on Feb 23, 1989 for the Crab. The Baksan data in the table is less impressive than in the first announcement [9]. After the reanalysis of the data we have found especially big nonstability of the timing system on Feb 23 [4] . When using a new algorithm of the reconstruction of arrival direction which we believe is better, some events went out from the accepting circle of $R = 2.5°$, some new came in. The new procedure affected also the background, the OFF counts.

The shifting of the events through the angular window border affected also the phasogram with the Crab pulsar period. The result occurred to be rather peculiar, showing a narrow peak in the 10-bin histogram (fig. 2). Unfortunately Baksan clock did not provide the precise absolute time, so real comparison with the KGF data cannot be made, the shapes of the histograms are quite different too. So I believe we do not have a reliable information on the time structure of the signal and should concentrate only on the DC data. Fig. 3 shows the map of excess density above background for Baksan data which looks reliable.

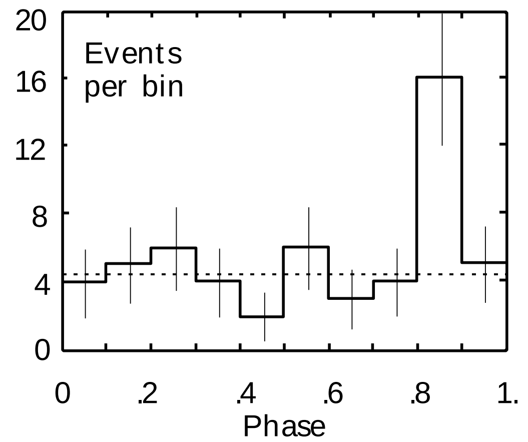

Fig.2 Phase diagram for 55 events from the Crab, 23 Feb 1989

But to evaluate the probability of all this being due to fluctuations the quality of Baksan data is not crucial. Actually Baksan recording served as a starting signal, just to indicate the time and direction. The product of four probabilities, presented in the Table 1 (excluding Baksan) is

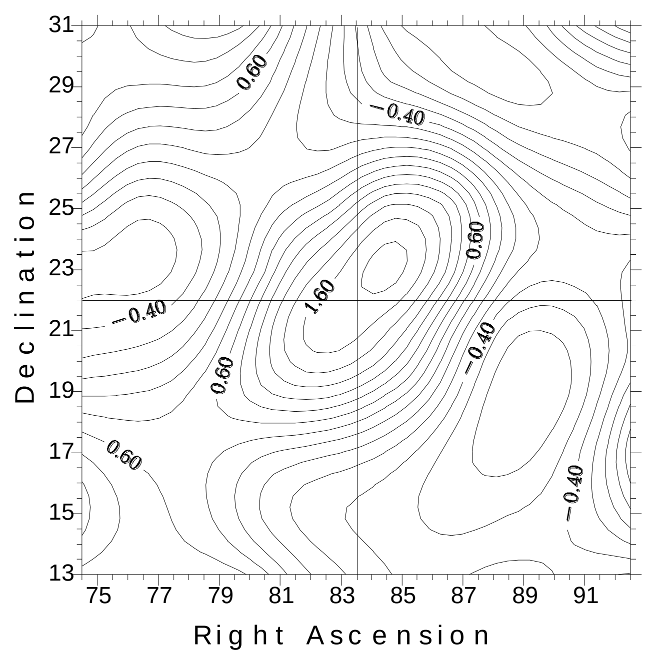

Fig. 3 Density map of the Crab Region (background subtracted).

$P_0 = 4 \cdot 10^{-9}$. The combined probability that all four independent increases were realized due to Poisson fluctuations should be calculated as:

$$P_c = P_0(1+\lambda+\frac{\lambda^2}{2}+\frac{\lambda^3}{6}) = 6\cdot 10^{-6}; \lambda = -\ln P_0 .$$

If we decide to include HEGRA and Akeno, which gave zero effect, in this procedure then the combined probability would increase by one order of magnitude, up to $4\cdot 10^{-5}$, but still this is small enough.

Though the Crab event Feb 23, 1989 looks as genuine one, there is an uneasy feeling because of:

1. Technical problems at Baksan array, which made the results flexible and dependable on the method of analysis. Could it be that other arrays involved may have similar problems?

2. The absence of the expected muon deficit at KGF array, that was the only one taking the muon data.

3. The theoretical difficulties to expect such a powerful outburst from Crab pulsar releasing the energy in 100 *TeV* gammas of ~ 10^{-39} erg during several hours.

5. Conclusions

1. The efficiency of the search for gamma ray sources using mainly the phase analysis and search for periodical emission should not be overestimated.

2. In UHE gamma ray astronomy the main problem is the reducing of the cosmic ray background. In VHE this approach occurred to be successful. In UHE technique the huge muon detectors are the most promising.

3. For the search of episodic (burst-like) emission in UHE range the most important thing is to have several EAS arrays in operation not so far one from another. The phenomenon certainly needs a simultaneous recording by several arrays. In the VHE range it is difficult to arrange but probably could be done by synchronized program.

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