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Detection of very high energy gamma rays from the CRAB source

THEMISTOCLE COLLABORATION[†]
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Abstract

The Themistocle experiment, which consists of an array of 18 Cherenkov telescopes located on the French Pyrenées, has successfully observed the emission of multi-TeV gamma rays from the CRAB source, with a significance corresponding to 6.5 standard deviations. The source is resolved with an accuracy of 2.5 mr ($\simeq$ 8 arc min.) per shower. The observation of the signal relies uniquely on the high angular resolution in determining the direction of the individual showers. The source is localized with the precision of the order of 0.5 mr ($\simeq$ 2 arc min.) in an energy range so far unexplored.
The energy of the gammas is estimated by measuring the amplitude of the Cherenkov signal detected by each of the 18 telescopes. The energy spectrum of the CRAB gamma source is determined in the range from 3 to 15 TeV. The results are compatible with a power extrapolation of the data available at lower energies ($<$ 1 TeV).

Talk given by P. Baillon[1] to the

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1 The Themistocle situation

From September 1990 onward, the Themistocle collaboration has been collecting data from high energy air showers pointing from the direction of the Crab nebula. The experiment is located at an elevation of 1650m in the Pyrenées near Perpignan in the south of France. It uses the facilities at the Themis solar power plant which is no longer in operation. 18 collecting mirrors of the plant have been replaced by 18 parabolic mirrors (diameter 800mm focal length 400mm),each equipped with a photomultiplier at its focal point. Each mirror support is equipped with two computer controlled motors which rotate the mirror around vertical and horizontal axes. This allows each mirror to follow a selected fixed point on the celestial sphere within 2 mrad. Fig. 1 shows the layout of the experiment on the Themis site, Fig. 2 the housing of a parabolic mirror with its photomultiplier.

2 Principle of the experiment

When a high energy cosmic ray of several TeV enters the upper part of the earth's atmosphere, it interacts at around 20 km in altitude and generates an extensive air shower mainly composed of electrons, positrons and low energy gamma rays (Fig. 3). At TeV energy, the shower has a small lateral extension. All the secondary particles remain close to the axis of the shower and parallel to the direction of the incident cosmic ray. Most of the electrons and positrons have a speed over the speed of light in the air and generate Cherenkov light with a maximal angle of 20 mrad. Simulations show that most of this light reaches the ground within 120m of the axis of the shower and form a conic type surface of $\pi/2 - 0.017$ rad. aperture. The axis of the cone is the shower axis. The conic surface is the front of a shock wave of photons which lasts only 3 ns or 1 meter in length. When this shock wave is in view of its mirrors, Themistocle samples it up to 18 points. A shower is in view of a mirror if its axis is aligned with the axis of that mirror within roughly 20 mrad and is less than 150 m away. Each telescope provides a measurement of the time of arrival of the shock wave and its amplitude. Using those informations, the position, the direction and the energy of the shower are evaluated.

3 Main features of the experimental apparatus

Each fast photomutiplier is equipped with a preamplifier with two outputs, one going to an ADC with a gain of 4 channels per photoelectron and the other to a constant fraction discriminator set at a threshold of 7 photoelectrons driving a TDC of 0.1 ns resolution. The signal from each mirror is delayed by a programmable delay unit (256 steps of 2 ns) set according to the direction of observation and

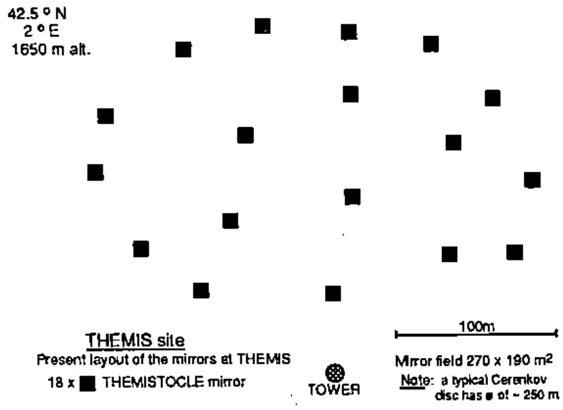

Figure 1: layout of the Themis site

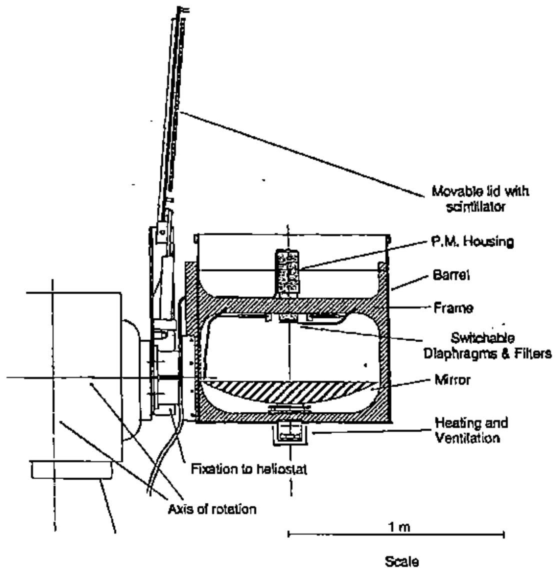

Figure 2: Themistocle Telescope

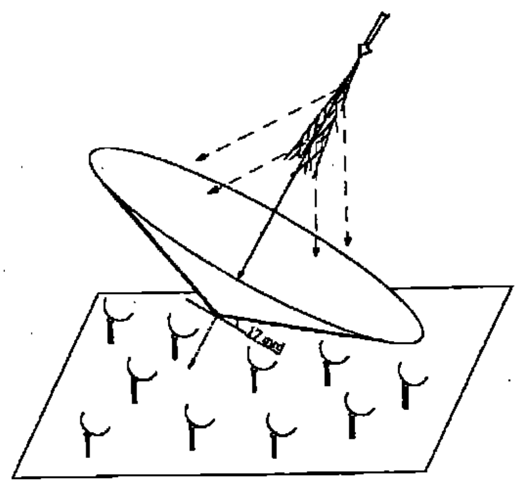

Figure 3: schematic view of an air shower detected by Themistocle

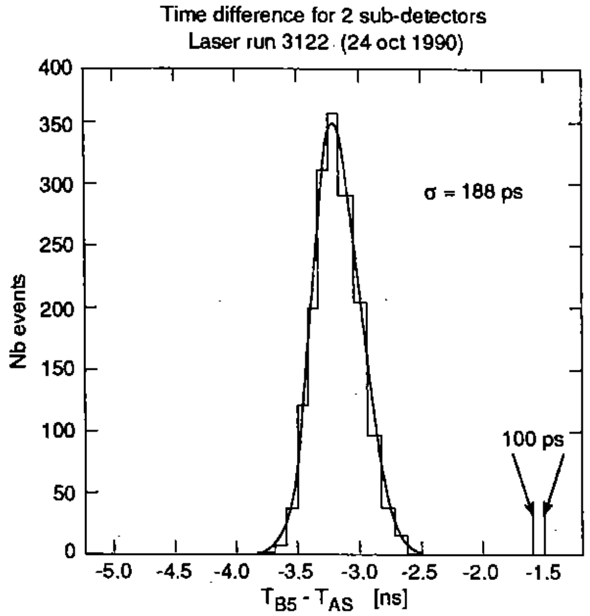

Figure 4: Themistocle time resolution

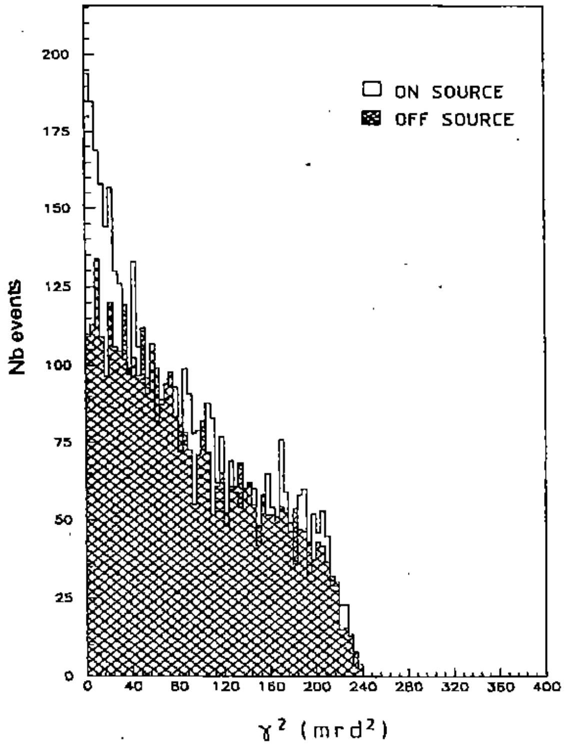

Figure 5: comparison between on the CRAB and off the CRAB γ^2 distribution

feeds a majority coincidence unit 50 ns wide. A trigger is generated when a 10 coincidence threshold is reached. Then the TDC's are started by a common signal and stopped by the output of the constant fraction discriminator. Fig. 4 shows the time difference between two mirrors when illuminated by a nitrogen laser pulse diffused from the tower overlooking the site. This laser pulse is used to synchronize all the TDC's and to evaluate the time resolution as a function of the number of photo-electron N_{phe}:

$$\sigma_t = \sqrt{0.17^2 + \frac{2.7^2}{N_{phe}}}\ (ns)$$

From simulations, the average resolution is estimated to be 14 m for the position of the shower apex and 3 mrad for its direction. The statistical energy resolution ranges from 20% at 3 TeV and 15% at 20 TeV for gamma showers with a systematic error of 20% and around 35% for accepted hadronic showers

4 Results on the CRAB nebula

The Themistocle collaboration has taken data on the CRAB nebula during the last two winters (90/91 91/92) while the nebula was within 30° of the zenith at night time. 155 hours were taken on source providing a sample of 76526 triggering showers as well as 190 hours off source (94278 showers). Each shower was analyzed by a program which fits a circular cone on it. The fit has 6 free parameters:

- position of the cone summit (3 parameters).
- direction of the axis (2 parameters).
- angle of the cone (1 parameter).

After the fit, the criteria for accepting a shower for further analysis are :

- at least 12 mirrors with data above the discriminator threshold,
- a cone angle between 12 and 22 mrad,
- an impact point in an ellipse centered on the field with axis length 200 and 190m,
- a χ^2 probability above 45%
- the angle γ lower than 15 mrad.

We designate by γ the angle between the direction of the source and the shower axis.
The selected sample corresponds to 5140 showers on-source and 6884 off-source. Fig. 5 shows the γ^2 distribution for on-source and off-source showers. A signal at $\gamma^2 = 0$ corresponding to the CRAB can easily be seen. The off-source distribution has been renormalized on the on-source data outside that signal peak.

A maximum likelihood analysis of the signal from the on-source data gives a confidence level corresponding 6.5 standard deviations for having detected gamma rays from the CRAB. The same procedure gives a width for the signal of 2.4 mrad compatible with our resolution and a zero width at emission. The fitted direction of the source itself is $(-0.1, 0.45) \pm 0.4 mrad)$ in a system centered on the source and is compatible with the Crab nebula's position within one standard deviation. There are 286 ± 55 showers in the signal. The ratio of signal to background is approximately 0.7. These results prove that our apparatus has achieved a resolution close to its nominal 2 mrd on electromagnetic air

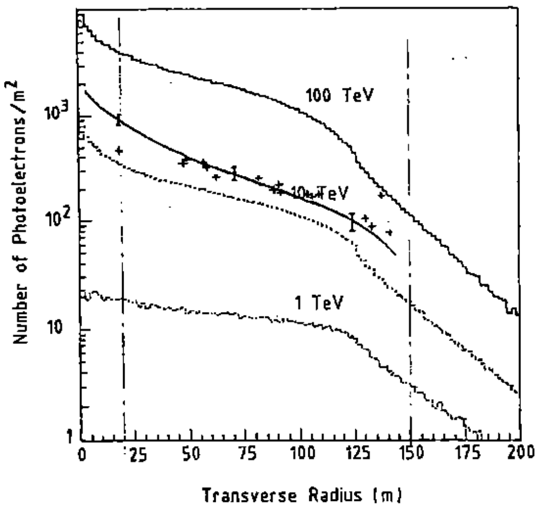

Figure 6: Amplitude Analysis of a typical shower

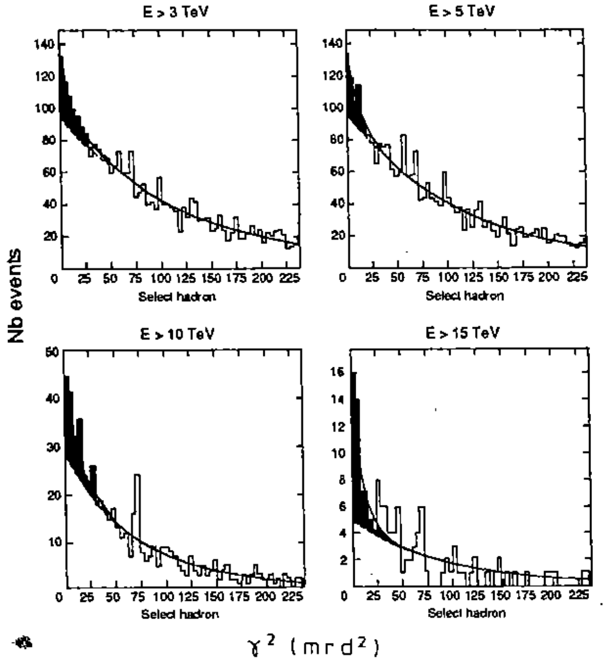

Figure 7: γ^2 distribution for the on-source selected showers

shower directions and demonstrates the excellent potentiality of such a device for precision measurements.

5 Energy spectrum

The ADC measurements provide an estimation of the energy of each gamma ray shower. By the analysis described in the previous paragraph, the position of each mirror relative to the shower axis is known within about 14 meters. The ADC measurements thus provide a series of at least 12 amplitude values along the Cherenkov wave front at several distances from the axis. By comparing these measurements with Monte Carlo generated showers at various energies, the energy of the shower can be interpolated. Fig. 6 shows a typical shower compared to a generated shower distribution. Only ADC measurements between 20 and 150 m from the axis of the shower are taken into account for this purpose. The energy of the shower is then given by the energy of the Monte Carlo shower which gives the best χ^2 on the data. The Monte Carlo showers were generated at 1,3,10 and 30 TeV at the average crab inclination, 28° from the zenith and interpolated for intermediate energies. In order to discriminate against hadronic showers, are rejected events which after subtraction of the two worst points still give χ^2 bigger than twice the number of remaining ADC's. This criteria is more efficient at the highest energies. Fig 7 shows the γ^2 distribution for the on-source selected showers at energies bigger than 3,5,10 and 15 TeV. In each of these histograms the signal amplitude is estimated by extrapolating the background below the signal. The acceptance is evaluated by Monte Carlo taking all cuts into account. The results from Fig. 7 combined with the acceptance yield the integral energy spectrum given in fig. 8. Those new measurements are in agreement

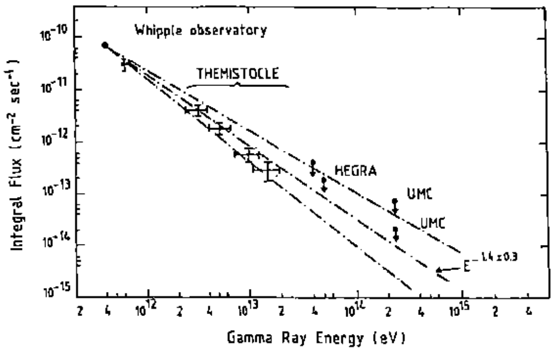

Figure 8: Integral spectrum of the γ ray flux coming from the CRAB

with a spectral index of -1.4 given in ref. [1] [4]. For energy higher than 20 TeV, the statistical errors become too big to allow any conclusion.

6 Conclusions

The previous results on the observation of the CRAB nebula[1][4] are confirmed at higher energy by the Themistocle experiment. The gamma ray flux of the CRAB is measured between 3 and 15 TeV by our experiment and is consistent with the spectral index of -1.4 ± 0.3 given by the Whipple Observatory [1].

The CRAB nebula is now the highest energy known source of particles > 15 TeV. But no conclusion on the flux behavior at energy higher than 20 TeV could be reached.

Acknowledgements

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