Proceedings of ICRC 2001: 2570 © Copernicus Gesellschaft 2001

ICRC 2001

# Search for point sources of gamma radiation above 15 TeV with the HEGRA AIROBICC array

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**Abstract.** A search for potential point sources of Very High Energy Gamma rays above 15 TeV has been carried out on the data taken simultaneously by the HEGRA AIROBICC and Scintillator arrays from August 1994 to March 2000. The list of sought sources includes Supernova Remnants, pulsars, AGNs and binary systems. The energy threshold is around 15 TeV. For the Crab Nebula, a modest excess of 2.5 standard deviations above the cosmic ray background has been observed. Flux upper limits (at $90\%$ c.l.) of around 1.3 times the flux of the Crab Nebula are obtained, in average, for the candidate sources. A different search procedure has been used for an all-sky search which yields absolute flux upper limits between 4 and 9 *crabs* depending on declination.

## 1 Introduction

In contrast to the success of Imaging Atmospheric Cherenkov Telescopes (IACTs) in detecting very high energy gamma rays from a number of discrete sources, wide-acceptance Air Shower Arrays, either of particle or Cherenkov light detectors, have to date produced very little evidence for any photon signal. Leaving aside some early claims, now discredited, the most significant reported detections are of about 5 standard deviations above the cosmic ray background fluctuations (Amenomori et al., 1999). The obvious disadvantages of these detectors with respect to IACTs are, first, their higher energy threshold, resulting from the limited reach of the particle component of showers in the atmosphere (in the case of particle detectors), or from the difficulty of discriminating the faint Cherenkov light flashes from the light of the Night Sky Background (NSB), integrated over a large fraction of the sky (of about 1 sr), and second, the lack of any powerful method to discriminate between gamma- and hadron-initiated showers. These handicaps are in part compensated by the large field of view, which allows for the monitoring of a large number of candidate sources at any time.

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## 2 The HEGRA Experiment

The HEGRA experiment (Barrio et al., 1998) is a multicomponent EAS detector located 2200 m a.s.l. in the Canary island of La Palma ($28.8^\circ$ N, $17.9^\circ$ W). The two sub-detectors relevant for this analysis are an array of 243 scintillation counters and the wide-acceptance Cherenkov array AIROBICC, consisting of 97 non-imaging 0.12 $m^2$ light detectors, both of them covering roughly an area of 200×200 $m^2$. The quoted figures refer to the most complete versions of the HEGRA arrays, which went through several upgrades during their lifetime, as well as through a fire which destroyed 89 stations in October 1997. AIROBICC was fully reconstructed after the accident, whereas the number of scintillator counters was reduced to 177, this being the final setup until the decommissioning of the two detectors in Spring 2000.

### 2.1 Shower reconstruction

The AIROBICC huts register the Cherenkov light flux and arrival times of the shower front whenever the trigger condition ($\geqslant$ 6 fired stations) is fulfilled. Only the data from detectors above threshold (roughly 5000 photons/$m^2$ in the spectral range 300–450 nm) are recorded. Similar data are registered by the scintillators, although only their amplitude signals (density of $e^{\pm}$ and secondary $\gamma_s$) are used, in the present analysis, for the determination of the shower core impact point on the ground. The shower direction is then determined exclusively from the timing of AIROBICC, by fitting the front shape to a cone whose axis goes through the predetermined core position. The dependence of the measured density of Cherenkov photons with the distance to the shower axis $r$ is fitted to an exponential $L_0 \cdot \exp(-r/R_L)$, where $R_L$ is the so-called *light radius*.

The angular resolution of AIROBICC improves from about $0.8^\circ$ at threshold to below $0.1^\circ$ for large showers firing the whole array, and its absolute pointing accuracy, cross-checked with the HEGRA system of 5 Cherenkov telescopes, was found to be better than $0.15^\circ$.

## 3 The Data Set

The data analyzed in the present work were registered in coincidence by the AIROBICC and Scintillator arrays during clear, moonless nights between August 1994 and March 2000. The period between July 1996 and June 1997 was excluded *a priori* due to a hardware error which worsened the detector's angular resolution significantly. After this exclusion, the data sample consists of a total of $290.8 \cdot 10^6$ events for which at least the shower direction was successfully determined, corresponding to an effective on-time of 3921 hours. The one-night average values of trigger rates and some reconstructed quantities like the *light radius* were used to identify and remove from the data set observation nights with poor atmospheric conditions, as well as those with various hardware problems resulting in abnormal shower reconstruction. About 1080 hours of observations were rejected on these grounds, reducing the data set to $216.0 \cdot 10^6$ reconstructed showers.

## 4 Data Analysis

For this analysis we define a standard sample of events by requiring that the $\chi^2$ value of the cone fit to the Cherenkov light front is smaller than 3. This cut removes about $9\%$ of the events from the data set. After this cut, the AIROBICC energy threshold, which can be calculated from the comparison of the observed rate of events and the known integral cosmic-ray flux, turns out to lie between 13 and 20 TeV for vertically incident photons, depending on the detector configuration (in particular, on the density of AIROBICC counters, which doubled in the 1997 upgrade).

Different searches have been performed on the selected sample of events. We have searched for signs of continuous and sporadic emission on a selected sample of sources and for continuous emission in the wide region of the Northern Hemisphere sky accessible to AIROBICC. The details are given in the next sections.

No use of gamma / hadron separation methods has been made in any of the searches detailed below, as in Karle et al. (1995), in contrast with other analyses (Götting et al., 1999). The reason is two fold. First of all, any such method requires optimal detector performance and observation conditions, since more shower parameters are needed other than incidence direction. Hence, tighter quality cuts must be applied to the data, both in the selection of valid nights (resulting in a loss of statistics, specially after the fire, due to the incomplete scintillator array), and in the event filter (increasing the effective energy threshold of the detector, which we want to keep as low as possible). On the other hand, separation cuts are always based in Monte Carlo simulations, which we have found uncertain in some aspects. Nevertheless, the increased statistics gives the present analysis a gain in sensitivity compared to previous results.

### 4.1 Search for predefined point sources

A sample catalog of candidates, both galactic and extragalactic, was used for point source searches, of sporadic and continuous excesses. The detailed list of 196 candidate sources, which can be found in Moralejo (2000), includes among others: all firm and tentative TeV detections, EGRET sources with error boxes smaller than 10 arc minutes, XTE ASM targets and small angular size SNRs. The analysis method used was based in counting the events in a circular ON region, around the position of the source. The optimal angular radius of this region is between 0.30 and $0.35°$, and has been computed independently for five data subsets defined by major changes in the detector's configuration. The radius was chosen as the one which would maximize the sensitivity of the method, after estimating the angular resolution for the period, taking into account its dependence with the number of fired huts and the composition of the standard sample in terms of this variable. The possible misspointing of the array has also been considered in this calculation.

| Source | $N_{ON}$ | $\hat{N}_B$ | $S(\sigma)$ | $E_{\gamma,umb}$ (TeV) | $\Phi_{\gamma,UL}$ ($10^{-13}$ cm$^{-2}$s$^{-1}$) |
|---|---|---|---|---|---|
| Crab | 4474 | 4305.01 | $+2.55$ | 16 | 5.94 |
| Mkn 421 | 3430 | 3460.62 | $-0.52$ | 17 | 2.11 |
| Mkn 501 | 5061 | 4983.80 | $+1.09$ | 17 | 3.14 |
| 2344+514 | 3638 | 3605.18 | $+0.54$ | 21 | 2.20 |

**Table 1.** *Results of the search for some relevant sources. Number of on-source and background events, significance of the excess, gamma-ray energy threshold and flux upper limit at* $90\%$ *C.L. are shown.*

The number of ON-source events is compared with the expected number of background events, computed from a Monte Carlo simulation. For the Monte Carlo simulation we have followed the lines of Alexandreas et al. (1993), generating 100 fake events for every true one, following the directional distribution of real data in local coordinates (which is stable within each of the five subsets mentioned above),

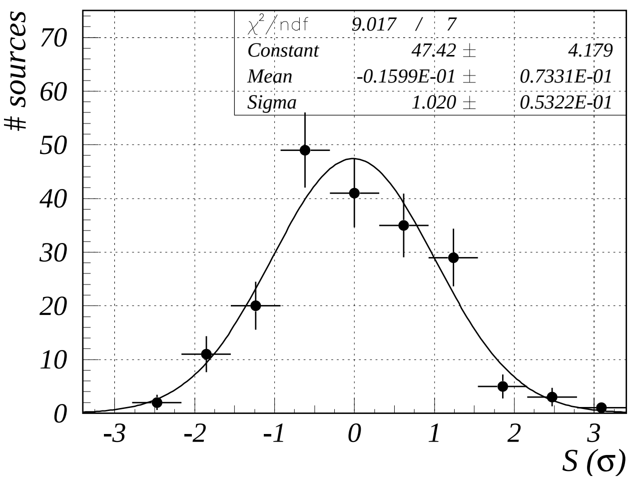


**Fig. 1.** *Distribution of significances for the 196 candidate sources.*

and with its same time coordinate. The significance of the excesses was then computed from the ON and background numbers using standard methods (Li and Ma, 1983). In order to compute a limit on the flux collected from each source, we did first extract a limit on the number of excess events in the ON bin, at $90\%$ C.L., using the formulas of Helene (1983). Comparison of this number with the estimated number of background events, and given the observed flux of Cosmic Rays around the source, one can convert this number into a limit to the flux of gamma rays impinging on the experiment from the chosen source.

The results for the search for continuous excesses were negative. Limits for the best known Northern Hemisphere TeV sources can be found in table1. Figure 1 shows the distribution of the significances of the excesses in the sample, which is compatible with the distribution which would result from the poissonian fluctuations of the isotropic cosmic ray background. As it can be seen in the plot, no significant excess is found in the data. The Crab nebula shows a modest excess of 2.5 standard deviations above the background (4474 observed events for an expected background of 4305.01), the second largest excess out of the 196 targets. If we interpret this excess as due to photons, the resulting integral flux for $E_\gamma > 16$ TeV, $(3.9 \pm 1.5\ _{\rm stat}) \cdot 10^{-13}{\rm cm}^{-2}{\rm s}^{-1}$ is roughly compatible with measurements from other experiments, as is shown in fig. 2.

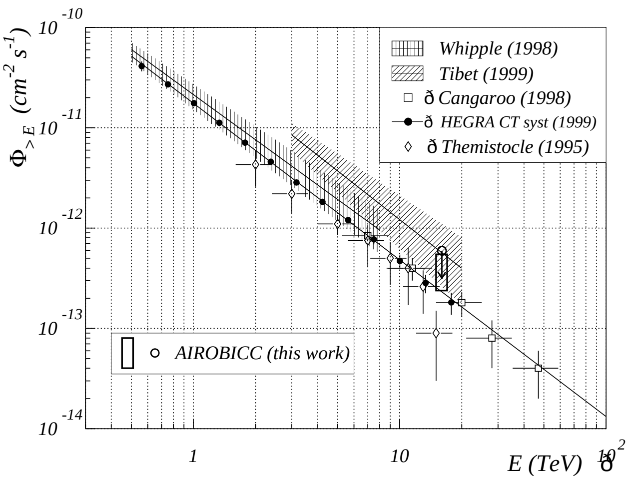


**Fig. 2.** *Very high energy integral spectrum of the Crab Nebula. AIROBICC result (90% C.L. flux upper limit and also flux estimate) is compared with measurements of other experiments.*

The procedure outlined above was also applied to the search for possible sporadic emission, by analyzing the event statistics for each candidate source night by night. With the data selection cuts defining our standard sample, the number of on-source events collected in one night for any given target was always less than 80 (since the time spent within the AIROBICC field of view is limited to about 5 hours). In order to overcome the difficulties associated with the small number of events, a different statistical treatment was applied to evaluate the significance of the observed excesses, being the relevant quantity $P$, the poissonian probability of obtaining, given the background, an excess at least as large as the observed one (Alexandreas et al., 1993). The resulting $P$ spectrum is shown in fig. 3, together with the expectation in the absence of sources (obtained from a Monte Carlo simulation). Both are found to be compatible. The little bumps in the distributions (for instance at $P \simeq 0.01$) are not statistical fluctuations, but a result of the discrete nature of the variables involved ($N_{ON}$, $\hat{N}_B$). Details can be found in Moralejo (2000). The smallest value found for $P$ is $3.7{\cdot}10^{-6}$. Once the number of analyzed nights and sources is taken into account, it can be seen that a pure background distribution would produce at least one such excess with a probability of $12\%$, and therefore no evidence for sporadic emission from any of the sources can be drawn.

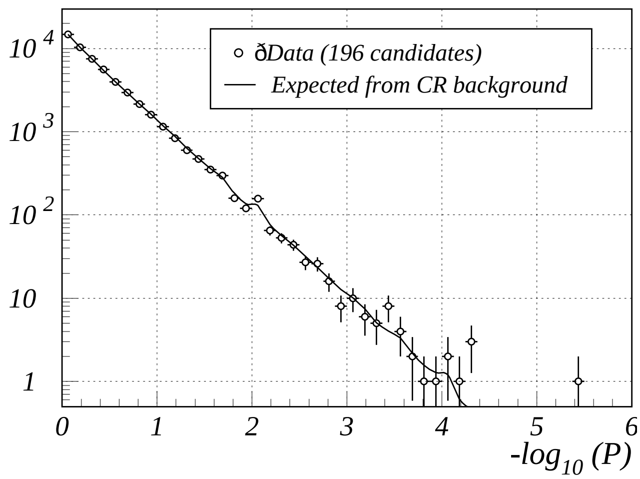


**Fig. 3.** *Search for 1-night excesses from the candidate sources. Spectrum of chance probabilities, compared to the one expected from an isotropic background.*

The daily results for Mkn 501 during its extraordinary 1997 outburst were carefully studied. The data set contained 36 valid nights in this period, none of which showed significantly low $P$ values for this source. No correlation was found either with the daily fluxes measured by the HEGRA collaboration at 1 TeV. The integrated AIROBICC data for this season shows no significant excess. Given the average flux of 4 Crabs at 1 TeV, and the AIROBICC sensitivity, the lack of detection can be attributed to the softening of the spectrum beyond a few TeV.

### 4.2 All sky search

Although handicapped by their high energy thresholds and lack of efficient gamma/hadron separation capabilities, air shower arrays have a strong point in all-sky searches. The field of view of AIROBICC is about one stereo-radian and its geographic position allows it to scan, within one year, the Northern Hemisphere in the region of declinations between 0 and $60^\circ$. For the all-sky map presented here, we have used a different search method than the one described for predefined candidate sources. The sky is divided into square bins of constant width in declination ($\delta$) and variable width in right ascension, proportional to $1/\cos(\delta)$, so that all of them cover the same solid angle ($1.17 \cdot 10^{-4}$ sr). The size of the bins is the same for all the observation periods, which makes the analysis simpler at the expense of a small loss of sensitivity. The use of a square bin instead of a round one has hardly any effect on the efficiency of the search (Alexandreas et al., 1993). To ensure that a significant fraction of the photons from any potential source is contained in at least one bin, nine overlapping grids have been built, by shifting the original one by one third of the bins' width in both axis. About $50\%$ of the events coming from a point source (the exact fraction depending on detector's configuration) is, in the worst case, contained in at least one of the bins. The background is estimated in the same way as described in §4.1. Once more, the distribution of significances for the $9 \times 61.2 \cdot 10^3$ non-independent search bins, which can be seen in fig. 4, does not deviate from the background expectation.

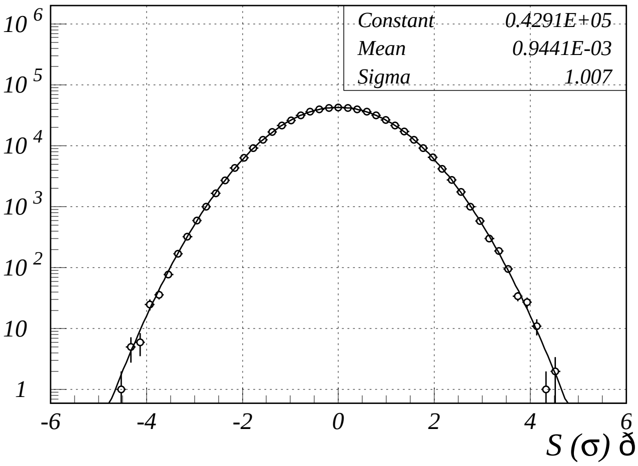


**Fig. 4.** *All-sky search for steady gamma-ray point sources in the Northern Hemisphere. Distribution of significances.*

Global flux upper limits (at $90\%$ C.L.) for point sources in the Northern Hemisphere are shown in fig. 5 as a function of declination. Since the average threshold varies from about 15 TeV at $\delta = 28^\circ$ to $\simeq 25$ TeV at $\delta = 0, 60^\circ$, the flux limits have been converted to units of the integral flux of the Crab Nebula for the corresponding energy (we have used for this purpose the measurements of the HEGRA system of Cherenkov telescopes, $\Phi_{\mathrm{Crab},>E} = 1.72 \cdot 10^{-11} \cdot (E/1\ \mathrm{TeV})^{-1.59}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$). In the declination band from 0 to $60^\circ$ the mean flux limits lie in the range 1.3 to 2.5 Crabs, and the absolute ones (from largest excesses seen in declination bands $5^\circ$ wide) are between 4.2 and 8.8 Crabs.

## 5 Conclusions

An analysis of 5 years of AIROBICC data, up to its decommissioning in Spring 2000, in search for emission from point-like sources has been presented. Flux upper limits (at

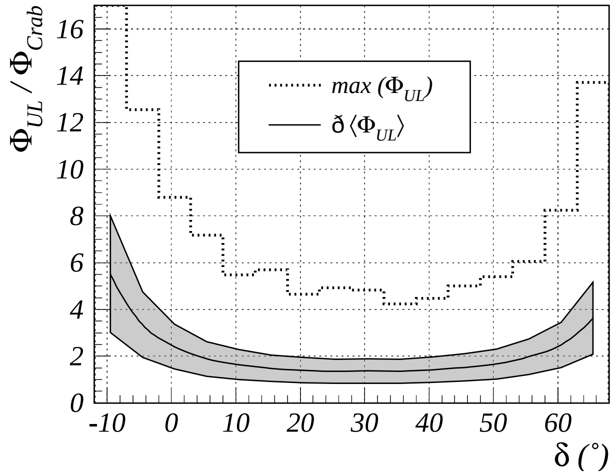


**Fig. 5.** *Flux upper limits (in units of the flux of the Crab Nebula) at $90\%$ C.L., for the emission from point sources. The mean, RMS (shadowed area) and the absolute limit (dotted, obtained from the largest observed excesses) are shown as a function of declination.*

$90\%$ C.L.) of around 1.3 Crabs have been obtained for steady emission from a catalog of candidate sources. No significant episode of emission in the time scale of one observation night has been found either from any of the candidates. Finally, absolute limits to continuous emission have been set for the declination band between 0 and $60^\circ$.

*Acknowledgements.* We wish to thank the authorities of the IAC (Instituto Astrofísico de Canarias) and the ORM (Observatorio del Roque de los Muchachos) for the permission to use the HEGRA site and the ORM facilities. This work was supported by the CICYT (Spain) and BMBF (Germany).

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