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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 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, in the band from $\delta = 0$ to $\delta = 60°$.

Key words. gamma rays: observations

1. Introduction

The part of the electromagnetic spectrum comprising gamma rays of energy above a few TeV is one of the least explored windows in Astronomy. Its study is of great importance in the understanding of very high energy non-thermal sources and for the determination of the origin of cosmic rays. This paper describes a systematic search for point sources emitting in energies above 15 TeV, using wide-acceptance air shower detectors.

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 detection is at the level of about five times the cosmic ray background fluctuations (Amenomori 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 powerful methods to discriminate between gamma- and hadron-initiated showers, in the absence of muon detectors. These handicaps are in part compensated by the large field of view, which allows for the simultaneous monitoring of a large number of candidate sources.

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* The full versions of Tables 1 and 2, including the coordinates of the sources, are available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr` (130.79.128.5) or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/390/39`

Readers interested in the basis, history and classical results of gamma-ray astronomy, in the range of energies studied in this paper, may consult the excellent review by Hoffman and collaborators (Hoffman 1999). Some recent results published by experiments other than HEGRA using wide-acceptance air shower detectors have been included in the bibliography (see for example references: Amenomori 1999; Atkins 1999; Atkins 2000; Borione 1997a; Borione 1997b; McKay 1993 and Wang 2001).

The HEGRA AIROBICC and scintillator arrays, decommissioned in March 2000, rank among the highest sensitivity air shower arrays constructed up to date. This paper presents the analysis of the data produced by them during most of their active life time, with respect to the search for point sources of very high energy gamma radiation. The present work updates previous results obtained on smaller data sets, obtained either using the same analysis procedure (Contreras 1998; Moralejo 2001) or with slightly different approaches (Prahl 1997; krawczynski 1997; Schmele 1998; Götting 1999).

Earlier publications dealing with the HEGRA arrays address: a description of AIROBICC performance (Karle 1995a), the search for gamma-ray point sources using the first year of data of the detector, a data set not included in this analysis (Karle 1995b), a search for Gamma Ray Bursts (Padilla 1998), an analysis of the Chemical Composition of Very High Energy (VHE) Cosmic Rays (Arqueros 2000), and two studies of the diffuse VHE gamma ray background (Aharonian 2001; Karle 1995c).

The description of the data analysis chain and the results of the experiment, presented in Sects. 3 and 5, constitute the core of this paper. The main features of the HEGRA arrays are described in Sect. 2, while Sect. 4 focuses on the particular data set used for this analysis.

2. The HEGRA experiment

The HEGRA experiment (Barrio 1998) is a multicomponent air shower detector located 2200 m a.s.l. on the Canary island La Palma (28.8° N, 17.9° W). The two sub-detectors relevant for this analysis (Fig. 1) are an array of 243 scintillation counters, and the wide-acceptance Cherenkov array AIROBICC (Karle 1995a), consisting of 97 non-imaging 0.12 m^2 light detectors, both of them covering roughly an area of 200×200 m^2. The scintillator array and AIROBICC became operational in 1988 and 1992 respectively, but the figures quoted above refer to the most complete versions of the HEGRA arrays, which went through several upgrades during their lifetime. In October 1997, a fire destroyed 89 stations. The AIROBICC array was fully reconstructed after the accident, whereas the number of scintillator counters was reduced to 182, this being the final setup until the decommissioning of the two detectors in Spring 2000.

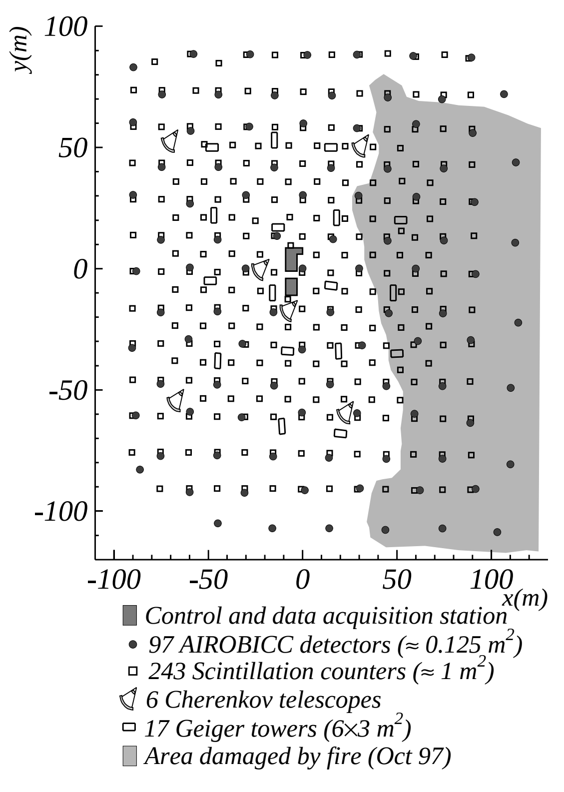

Fig. 1. Schematical view of the HEGRA experimental area, the zone depicted in dark grey was burnt during the fire of Autumn 1997.

Primary cosmic rays (including photons) impinging on the atmosphere initiate extensive air showers (EAS) of relativistic particles. The HEGRA scintillators detect charged particles at ground level, as well as secondary gammas, converted in a thin lead layer placed on top of each detector. The light produced in the plastic scintillator is viewed from below by one or two photomultipliers installed at the bottom of a light-tight hut, which allows the operation of the array even in daylight. AIROBICC stations consist of a 20 cm diameter hemispherical photomultiplier, coupled to a Winston cone light collector, receiving directly Cherenkov radiation from EAS. Therefore, and in contrast to the scintillator array, AIROBICC can work only during dark nights, a fact which restricts its operation to a maximum of about 15% of the total time. In the present work, only data registered in coincidence by both arrays have been analyzed (a similar study using only scintillator data can be found in Schmele 1998).

3. Shower reconstruction

The AIROBICC stations register the Cherenkov light flux and arrival times of the shower front at the huts whenever the trigger condition ($\geqslant 6$ or 8 fired stations within 200 ns, depending on the detector configuration) is fulfilled. The resulting trigger rate varies between 20 and 30 Hz. 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 scintillation counters for the particle shower front.

The shower core impact point on the ground is estimated from the distribution of the scintillator amplitude signals (density of $e^{\pm}$ and secondary γ_s), via a simple center of gravity procedure, and from the Cherenkov light distribution as measured by AIROBICC, through a fit in which a radial symmetric light distribution is assumed and where the core coordinates are free parameters. Once the core position is known, the shower direction is reconstructed exclusively from the timing of AIROBICC, by fitting the time structure of the Cherenkov light front to a cone (of fixed semi-angle 88.969°) whose axis goes through the core. The fit procedure is iterated three times for every shower. After each step, signals lying far from the fitted shower front, probably coming from NSB fluctuations, are tagged and not included in the following one. The scintillator array timing data is not used for the direction determination due to its intrinsically poorer time resolution. The shower direction thus obtained in local coordinates is transformed to celestial coordinates by using the UTC time stamp on each event, which is provided by a Rubidium clock.

The lateral distribution of $e^{\pm}$ and secondary γ_s as measured by the scintillator array is fitted to an NKG formula, from which the shower size and age are derived. Finally, 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*. These parameters are used, in the present analysis, only to identify nights with poor observation conditions, by comparison of their distributions with those obtained from a Monte Carlo simulation. The development of showers in the atmosphere was simulated using the CORSIKA code, version 4.068 (Capdevielle 1992). Details on the detector simulation can be found in Martínez (1995).

3.1. Detector calibration

Special calibration runs, interleaved with data acquisition every twenty minutes, were used to obtain the pedestals of the ADC channels, as well as the conversion factors to translate the TDC channels readout into ns.

The effect of temperature variations in the propagation speed of signals from the huts to the central data acquisition station was monitored by using light pulses produced during the calibration runs by a small LED located above every photomultiplier. The delays measured in this way were fine-tuned for every run by studying the mean deviations of each detector with respect to the fitted shower front, in a preanalysis of extensive, well measured, showers. An estimate of the time resolution of the detectors is also obtained in this preanalysis, allowing us to weight them accordingly in the final shower reconstruction.

The conversion factors from ADC counts to number of particles reaching the scintillation counters were computed from the position of the single MIP (Minimum Ionizing Particle) peak in the individual counters spectra, registered in real, shower-triggered events. The relative gains of the AIROBICC stations were adjusted by normalizing the high-amplitude tails of their ADC spectra (in the region, well above threshold, where the efficiency of all the detectors is 1), once the known nonlinearities in the amplification chain are corrected.

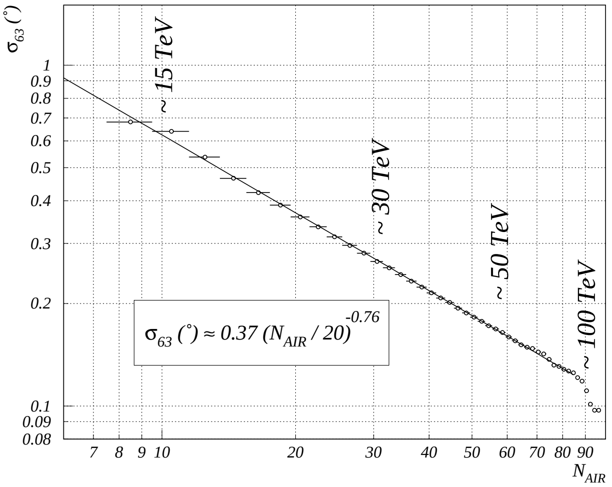

Fig. 2. Estimated angular resolution for the final configuration of AIROBICC as a function of the number of fired huts. The parameter σ_{63} is the angular radius within which 63% of the events from a point source would be contained. The corresponding energies of gamma primaries are shown.

3.2. Angular resolution

A delicate point is the computation of the angular resolution of the detector, since no source was found by the experiment, impeding the use of real data to this end. A three step procedure was followed using Monte Carlo simulations and real data. First the data set was divided in periods of stable hardware configuration, within which the angular resolution can not change significantly. Then, for each real data run the AIROBICC array huts were divided into two subsets in a configuration resembling that of chessboard black and white squares. Events were reconstructed independently with each subarray and the two resulting directions compared. The same procedure was applied to Monte Carlo simulated showers, where the true direction, and hence the angular resolution, is known. It was finally assumed that the relation between the angular resolution and the outcome of the chessboard procedure observed in the Monte Carlo holds in the real data. In this way, the angular resolution as a function of the number of fired stations was obtained for each of the subperiods mentioned above. The result for the last of them is shown in Fig. 2. The angular resolution thus found improves from about 0.8° at threshold to below 0.1° for large showers firing the whole array.

An upper limit on the pointing inaccuracy was set comparing the directions reconstructed by the HEGRA system of 5 Cherenkov Telescopes (Daum 1997) with those provided by AIROBICC for a set of common events (Fig. 3). The absolute pointing of the IACT system, which has successfully detected several TeV point-like sources, is known to be better than 0.01° (Pühlhofer 1997). With this procedure, the AIROBICC mispointing was found to be less than 0.15° at the 3 σ confidence level.

4. The Data Set

The data analyzed in the present work were registered in coincidence by the AIROBICC and scintillator arrays during clear,

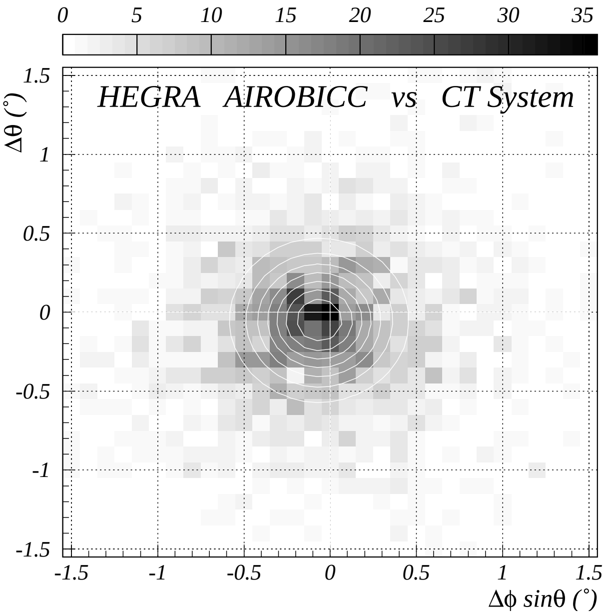

Fig. 3. Relative deviation of shower directions determined by the HEGRA IACT system, with respect to the direction reconstructed by AIROBICC. ϕ and θ are the azimuth and the zenith angle of the registered showers. The plot shows a sky projection, in which the (0,0) point stands for the direction determined by AIROBICC. The z axis corresponds to the number of events.

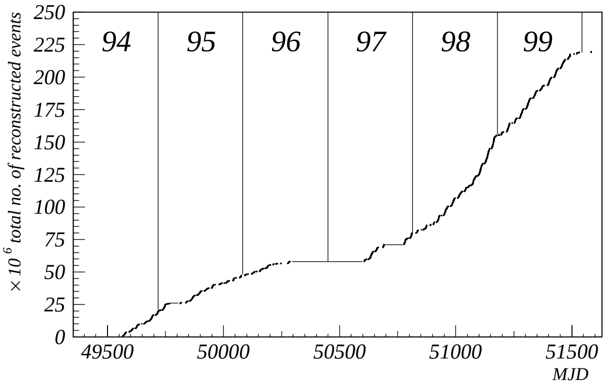

Fig. 4. Integrated number of events collected as a function of time, from the year 1994 to 2000. The different slopes correspond to changes in the detector configuration which modify the trigger rate.

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 ($E > E_{\gamma,\rm thr}$) at 90% C.L. are shown.

Source	$N_{\rm ON}$	$\hat{N}_{\rm B}$	$S\,(\sigma)$	$E_{\gamma,\rm thr}$ (TeV)	$\Phi_{\gamma,\rm UL}$ (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
1ES1426+428	3916	4029.87	−1.79	17	1.21

moonless nights between August 1994 and March 2000. The evolution of the number of reconstructed showers is presented in Fig. 4. 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 290.8×10^6 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 of some reconstructed quantities like the effective radius of the Cherenkov light pool (*light radius*, see Sect. 3), 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 219.7×10^6 reconstructed showers.

5. Data analysis

For this analysis we define a standard sample of events by requiring that the χ^2 per degree of freedom 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 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 was doubled in the 1997 upgrade). This can be inferred from the comparison of the known integral cosmic-ray flux and the observed rate of events, which provides us with a sort of average hadron threshold, then converted to a gamma threshold with the help of the Monte Carlo simulation. The threshold is more or less constant up to a zenith angle $\theta = 15°$, and then increases rapidly with θ (at 30° it is already 50% higher than at zenith).

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 following sections.

No use of gamma/hadron separation methods has been made in any of the searches detailed below, as in Karle (1995b), in contrast with other analyses (Götting 1999). The reason is that any such method requires optimal detector performance and observation conditions, since more shower parameters are needed other than incidence direction. Hence, tight 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). Nevertheless, the large statistics gives the present analysis a gain in sensitivity compared to previous ones.

Detailed studies on the gamma/hadron separation capabilities of non-imaging air-shower arrays can be found in Prahl (1999) and Moralejo (2000).

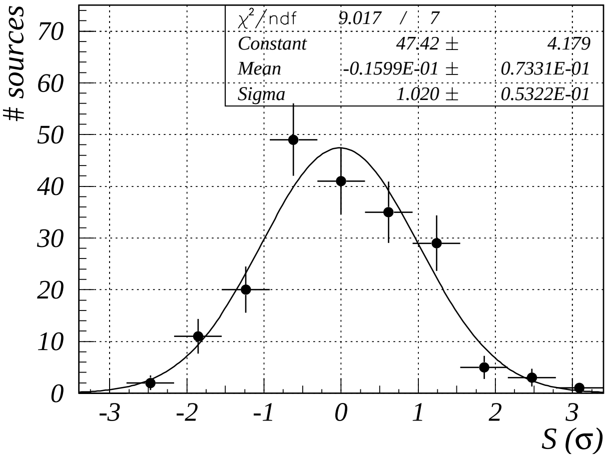

Fig. 5. Distribution of significances for the 196 candidate sources.

5.1. 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 within the AIROBICC field of view, which can be found in Moralejo (2000), includes mainly:

- All firm and tentative TeV detections (Table 1).
- Sources monitored regularly by the RXTE ASM (ASM 1997).
- A set of nearby active galaxies monitored by the HEGRA Cherenkov telescopes (see Table 2).
- EGRET sources with error boxes smaller than 10 arcmin, from the third EGRET catalog (Hartman et al. 1999).
- Well localized GRBs, from Greiner (2000).
- X-Ray binaries, from Guseinov (1999).
- Supernova remnants with small angular extension from Green (1997).

The analysis method used was based on counting the events in a circular ON region around the position of the source. The optimal angular radius of the ON region, which is between 0.30 and 0.35°, has been computed independently for five data subsets defined by major changes in the detector 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 maximum mispointing of the array has also been considered in this calculation.

The number of ON-source events is compared with the expected number of background events, computed from a Monte Carlo simulation. For the simulation we have followed the lines of Alexandreas (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), and with its same time coordinate. The significance of the excesses was then computed from the ON and background numbers using standard methods (Li & Ma 1983). In order to compute a limit on the flux collected from each source, we did first derive a limit on the number of excess events in the ON bin, at 90% C.L., using the formulas of Helene (1983). Comparing this number with the expected number of background events, and given the known flux of Cosmic Rays around the source, the limit on the number of excess events is converted into a limit on the flux of gamma rays from the chosen source.

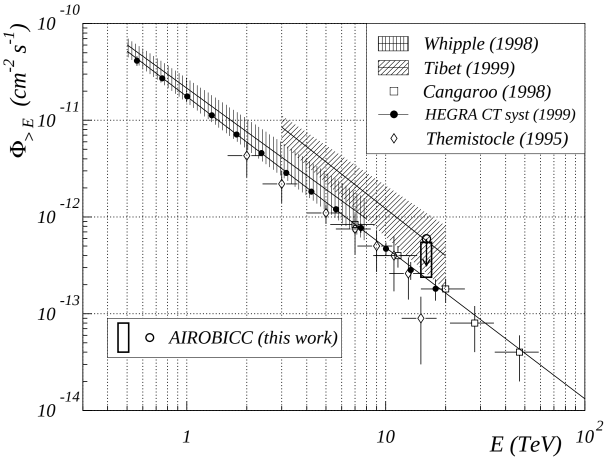

Fig. 6. Very high energy integral gamma-ray spectrum of the Crab Nebula. AIROBICC result (90% C.L. flux upper limit and also flux estimate) is compared with measurements of other experiments. The HEGRA IACT system measurement is published in Aharonian (2000).

The results for the search for continuous excesses were negative. Limits for the best known northern hemisphere TeV sources can be found in Table 1, those for the full list have been compiled in Table 2 (available at the CDS, see note to the title). Figure 5 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 hadronic 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, $(3.9 \pm 1.5_{\,\mathrm{stat}}) \times 10^{-13}$ cm^{-2} s^{-1} is roughly compatible with measurements from other experiments, as is shown in Fig. 6.

The average gamma energy threshold of the observations for each source depends on its declination, since it determines the mean elevation of the source above the horizon. The declinations of the 196 selected objects are distributed within 40 degrees around the geographical latitude of La Palma, resulting in thresholds between 15 and 70 TeV (with only 15% of sources above 30 TeV). We can then convert the flux limit derived for each source to units of the integral flux of the Crab Nebula for the corresponding energy (in the following, *crabs*). We have used for this purpose the measurements of the HEGRA system of Cherenkov telescopes (Aharonian 2000), $\Phi_{\mathrm{Crab},>E} = 1.72 \times 10^{-11} \cdot (E/1\ \mathrm{TeV})^{-1.59}$ cm^{-2} s^{-1}. The distribution of the flux upper limits for the 196 sources peaks at about 1.3 *crabs*. The detailed list of the results can be found in Table 2.

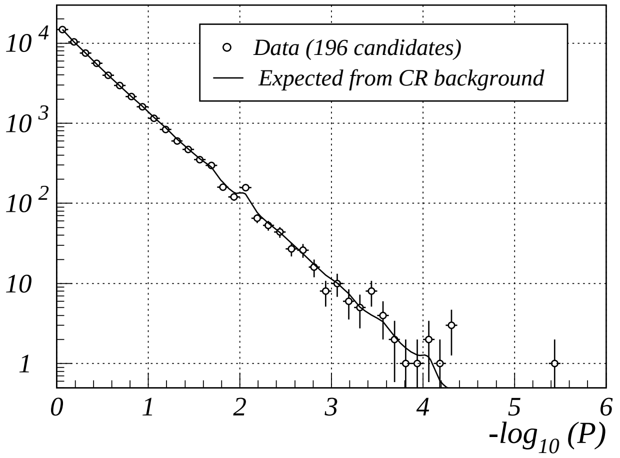

Fig. 7. Search for 1-night excesses from the candidate sources. Spectrum of individual chance probabilities (see text), compared to the one expected from the fluctuations of the hadronic cosmic ray background.

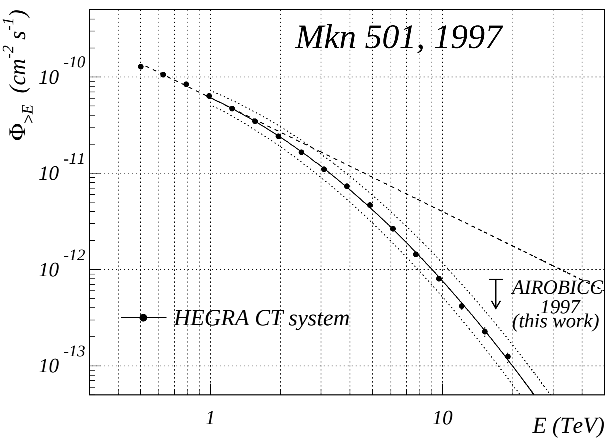

Fig. 8. Integral spectrum of the source Mkn 501 during its extraordinary outburst in the year 1997, as measured by the HEGRA IACT system between 0.5 and 20 TeV (Aharonian 1999b). Its simple extrapolation (following a power law of spectral index −1.18, obtained fitting the points between 0.5 and 1.5 TeV) to higher energies is compared with the limit presented in this work.

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: the relevant quantity is now P, the poissonian probability of obtaining, given the background, an excess at least as large as the observed one (Alexandreas 1993). The resulting P spectrum is shown in Fig. 7, 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 ($N_{\rm ON}$, $\hat{N}_{\rm B}$). Details can be found in Moralejo (2000). The smallest value found for P is 3.7×10^{-6}. Once the number of analyzed nights and sources is taken into account, giving a total of 53269 trials, it can be seen that a pure background distribution would produce at least one such excess with a probability of 0.12, and therefore no evidence for sporadic emission from any of the sources can be drawn.

The daily results for Mkn 501 during its extraordinary outburst in 1997 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 (Aharonian 1999a; Aharonian 1999c). 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. This fact is shown graphically in Fig. 8, where the AIROBICC limit is compared with the average spectrum measured during the outburst by the HEGRA system of Cherenkov Telescopes (Aharonian 1999b).

5.2. 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°. 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 (δ) and variable width in right ascension, proportional to $1/\cos(\delta)$, so that all of them cover the same solid angle (1.17×10^{-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 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 axes. 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 Sect. 5.1. Once more, the distribution of significances for the $9 \times 61.2 \times 10^3$ non-independent search bins, which can be seen in Fig. 9, does not deviate from the background expectation.

Global flux upper limits (at 90% C.L.) for point sources in the northern hemisphere are shown in Fig. 10 as a function of declination. The average gamma energy threshold varies from about 15 TeV at $\delta = 28°$ to $\simeq 25$ TeV at $\delta = 0$ and $\delta = 60°$. In this declination band the mean flux limits lie in the range 1.3 to 2.5 *crabs*, and the absolute ones (derived from the largest excesses seen in declination bands 5° wide) are between 4.2 and 8.8 *crabs*.

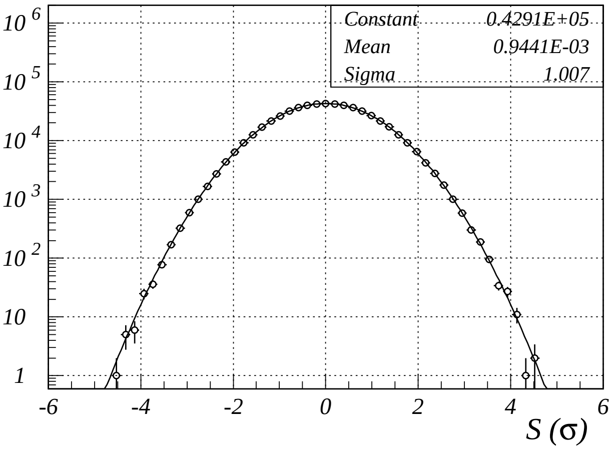

Fig. 9. Distribution of significances in the all-sky search for steady gamma-ray point sources in the northern hemisphere.

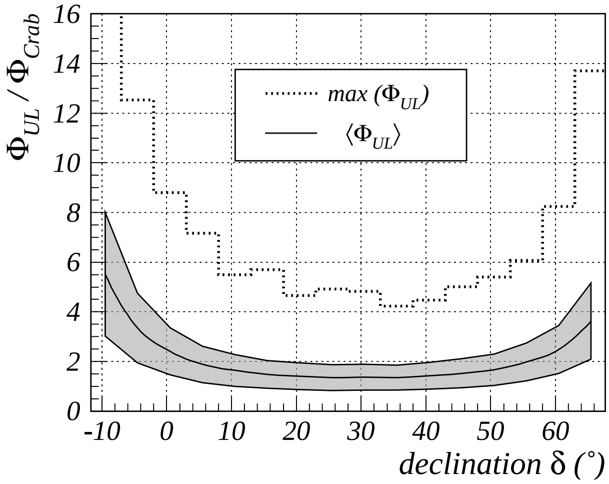

Fig. 10. Flux upper limits (in units of the flux of the Crab Nebula) at 90% C.L., for the emission from point sources. The mean, RMS (shadowed area) and the absolute limit (dotted, obtained from the largest observed excesses) are shown as a function of declination.

This analysis improves the results of the all-sky search presented in Götting (1999), based on a two-year data set taken with the first version of AIROBICC (with 49 stations). Although a gamma / hadron separation method was used in that previous work, the increased statistics of the present analysis results in an improvement of the flux upper limits, assuming Crab-like spectra (to account for the different energy thresholds), of about 15%.

6. Conclusions

An analysis of AIROBICC data taken within 5 years, up to its decommissioning in Spring (2000), in search of emission from point-like sources has been presented. No compelling evidence for any gamma signal was found. Flux upper limits (at 90% C.L.) of typically around 1.3 times the flux of the Crab Nebula have been obtained for the steady emission from a catalog of 196 candidate sources. No significant episode of emission on the time scale of one observation night has been found from any of the candidates. Finally, an all-sky search has yielded absolute flux upper limits between 4.2 and 8.8 *crabs*, depending on declination, for continuous emission in the fraction of sky accessible by the detector.

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