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A Partial Sky Survey for Point Sources of 20 TeV Gamma Rays Using the HEGRA AIROBICC and Scintillator Arrays

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Abstract

A survey of the largest part of the northern sky in search of unknown gamma-ray sources is carried out using 2 years of data simultaneously recorded with the HEGRA scintillator and AIROBICC arrays. A special procedure is applied which retains the full sensitivity as obtained in searches for selected candidate positions. The used technique enables the search for integral flux excesses of single sources and source populations. Global flux limits for point sources are derived. In addition, tests on variable fluxes from arbitrary positions are performed.

1 Introduction

Particle detector arrays using the shower front sampling technique have played an important role at the advent of VHE and UHE γ-ray astronomy. Although γ-ray point sources around $1\,\mathrm{TeV}$ could only be established beyond any doubts by Imaging Air Cherenkov Telescopes (IACTs) during the past decade, wide angle array detectors are further developed and are today more sensitive by roughly one order of magnitude than the installations 10 years ago. In contrast to the narrow field of view of the IACTs, these arrays observe a large fraction of the sky simultaneously. In spite of their lower sensitivity in a search for selected single γ-ray point sources when compared to IACTs (which is mainly caused by a higher energy threshold of the arrays) they offer a unique possibility for detections of unknown or sporadically active sources with low duty cycles.

The HEGRA wide-angle Cherenkov array AIROBICC especially takes advantage of the excellent angular resolution of a Cherenkov light detector. In addition, the combination with the scintillator array data allows for a γ-hadron separation to a certain degree.

This contribution reports on a sky survey for γ-ray point sources carried out with the combined data of the HEGRA scintillator and AIROBICC arrays of about 2 years. After a brief introduction of the detector and the data base, the newly developed method for the derivation of on-source and background statistics on a search grid is described. Then the results of the search for DC excesses, and a new procedure for tests on variability are presented. Finally, in the last section a summary will be given.

2 The Experiment and the Data Set

The HEGRA multicomponent air shower detector is located at the Canary island La Palma at 28.8° N, 17.9° W, $2200\,\mathrm{m}$ a.s.l.. A description can be found elsewhere (Lindner 1997). For the analysis presented here, the HEGRA matrix (in the state of 1995) of 219 scintillation counters ($\sim 1\,\mathrm{m}^2$ each, on an area of about $180 \times 180\,\mathrm{m}^2$, see Krawczynski 1996), and the so called AIROBICC array of 49 wide-angle Cherenkov light detectors (Karle 1995), placed on the same area, were used. Data of both arrays combined consist of the arrival times of the Cherenkov light cone, the particle shower front, as well as the Cherenkov light density, and the number of particles for each station and each triggered event.

The resulting energy threshold is approximately $15\,\mathrm{TeV}$ for γ-ray showers of vertical incidence when AIROBICC is operational during moonless nights. For AIROBICC, the average angular resolution was determined to be 0.31°. The data selection and reconstruction including the γ/hadron separation pearl follows the description given in Prahl 1997. The data used for these analyses (consisting of $\sim 67 \cdot 10^6$ events) were taken with the HEGRA arrays during the time interval from December 1993 until September 1995.

3 The Search Grid, the On-Source and Background Statistics

In the method to search of single pre-selected γ-ray point sources, a circular on-source region of an optimal radius of $0.41°$, and a ring-shaped background region with an inner radius of $1.0°$ and an outer radius of $2.4°$, were used to determine on-source and background statistics (see Prahl 1997). Since the acceptance of AIROBICC drops quickly for zenith angles $\vartheta \gtrsim 30°$, a cut on the zenith angle $\vartheta \leq 30°$ for the *source position* was applied, in order to get a consistent background estimation from the background region content.

For the survey for γ-ray point sources presented here, a search grid with a spacing of $0.1°$ in both declination and right ascension is defined. The declination range is limited to $-3.8° \leq \delta \leq 53.8°$, leading to $1.73 \cdot 10^6$ considered directions in a total solid angle of $\Omega_{\text{scan}} = 4.66\,\text{sr}$, which corresponds to approximately 37 % of the celestial sphere. Ideally, each search grid direction (SGD) should be treated like a pre-selected source position, but the use of the on-source and background regions precisely as defined above for single sources would cause the computing time getting inacceptably large.

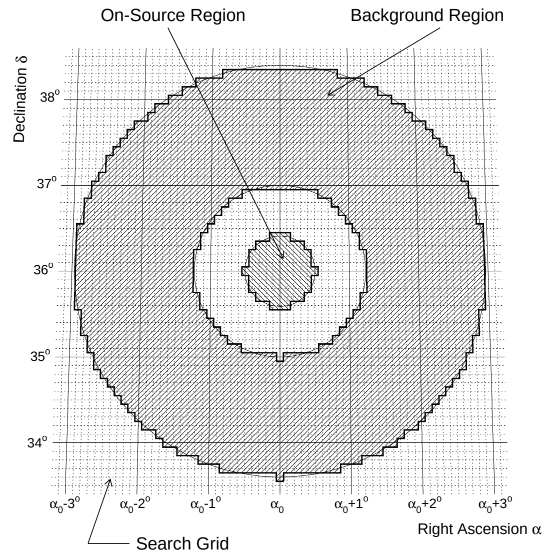

Figure 1: *The source and background region approximated from $0.1° \times 0.1°$ sized cells for the search grid direction (SGD) at the center of the figure (declination $\delta = 36°$). The corresponding ideally circular region boundaries are drawn with thin lines.*

For this reason, on-source and background regions are approximated from *directional cells* tiling the celestial sphere. Those cells are defined to have a size of $0.1° \times 0.1°$ in the equatorial coordinates, each being centered on one SGD. Fig. 1 shows this construction for one example.

Each SGD is represented by two scalers for counting on-source and background statistics, respectively. For each event in the data sample, the directional cell in which it falls is determined, and the corresponding counters for on-source resp. background regions where this cell belongs to are incremented, provided the SGD in question passes the $\vartheta \leq 30°$ cut. This incrementation procedure can be completely performed with adequate loop constructions using pre-calculated lookup tables for the loop ranges, which define the region boundaries. Thus practically all trigonometric computations are eliminated during the data processing. In this way, apart from the slightly different definition of on-source and background regions, every SGD is treated like it is described in Prahl 1997.

Taking into account the point spread function of AIROBICC, the above procedure ensures almost perfect sensitivity on any point source present in the considered declination interval. The introduced losses in sensitivity compared to an ideal treatment of a point source due to the changed on-source region definitions and the typical off-spacing of the closest SGD amount to approximately 1%.

4 Results from the Survey for DC γ-Ray Excesses

After the processing of the combined AIROBICC and scintillator data with applied γ-hadron separation pearl, for each SGD the DC significance $S_{\text{DC pearl}}$ was calculated using the Likelihood ratio method of Li & Ma 1983, taking the exact ratios of the solid angles of the on-source and background regions for each SGD into account. Fig. 2 shows the distribution of the significances for all considered SGDs. It should be mentioned that the distribution exhibits strong oversampling. The number of independent SGDs N_{indep} can be roughly estimated from the ratio of the scanned region to the size of the on-source regions, leading to $N_{\text{indep}} \approx 29 \cdot 10^3$.

The width of the fitted Gaussian in Fig. 2 of 1.003 therefore is in perfect agreement with a standard normal distribution. The faint (but statistically moderately significant) bias of the mean value of the fitted distribution of 0.02 from zero is a consequence of the curved acceptance function, yielding a slightly underestimated background determination for the on-source region in the procedure described in the last section.

Fig. 2 shows explicitly, that no source positions with high significances have been found to give a clear signal. The highest value was obtained at $\alpha = 142.1°$, $\delta = 50.9°$, yielding 4.86 σ. (The second entry greater than 4.8 σ stems from a neighbouring SGD.) Since there is no γ-ray point source yielding a DC significance greater than 4.9 σ in the sky region being observed by AIROBICC in the considered time interval, upper limits on the γ-ray flux shall be derived.

These limits are calculated for all SGDs on a 90 % confidence level, using the procedure as defined in Helene 1983 which is based on a Bayesian approach. The specification of upper limits on the γ-ray flux for each of the $1.73 \cdot 10^6$ SGDs is impracticable, but the background statistic and hence the sensitivity for SGDs with the same declination is similar. Therefore declination bins of 2° width are scanned for those SGDs yielding the highest upper limit. Additionally, the mean value and the spread are calculated for each bin.

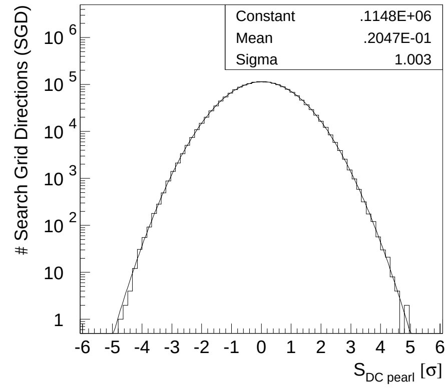

Figure 2: *The spectrum of DC significances after applying a cut using the γ-hadron separation* pearl *for all considered $1.73 \cdot 10^6$ SGDs. The histogram shows the data. The curve is the fitted Gaussian.*

The resulting upper limits on the flux, together with the γ-ray threshold energies for which these limits are valid, are shown in Fig. 3. In the energy regime around 20 TeV, these are the first global upper limits for γ-ray point sources of a large fraction of the sky.

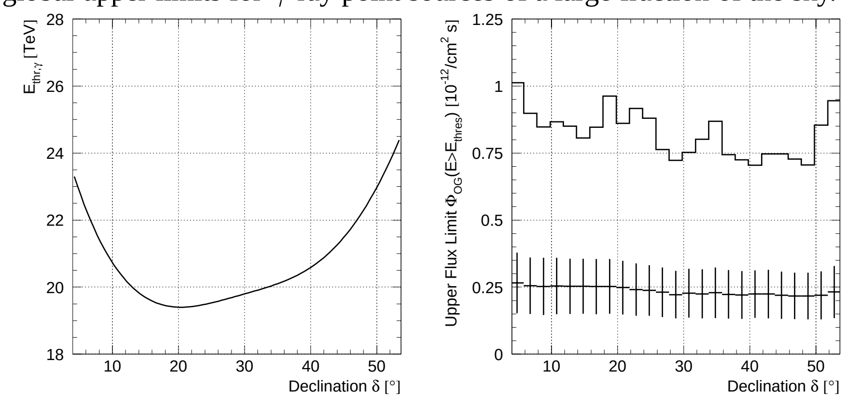

Figure 3: *The energy threshold $E_{\rm thres}$ for γ showers as a function of the declination δ (left). The resulting upper limits on the flux for declination bands with a width of 2° (right). The crosses show the mean values per declination bin, with the error bars indicating the spread of the underlying SGD population. The histogram shows the maximal values found in each bin. All results are calculated for a confidence level of 90 %.*

A further test on populations of sky positions having moderate DC significances of more than about 3 σ (which is nontrivial due to the oversampling) that is not described here yield no significant effect either. Details about this procedure can be found in Prahl 1999a. However, a look at the leading edge of the distribution shown in Fig. 2 already shows that there is no prominent deviation from the expectation above 3 σ present.

5 Tests on Variable Fluxes

In a second data processing the SGDs are tested on variable fluxes with two different unbinned methods. The first one is the Kolmogorov test comparing the cumulated distribution functions of on-source and background events in time. The second one is a newly developed differential mutual test named *exp-test* of the time series of the events in on-source and background regions. While the Kolmogorov test is most sensitive on one uninterrupted actitity time interval if the DC flux is kept fixed, the exp-test is designed such that the result is unaffected by such interruptions as far as possible, thus being well suited to dectect irregular burst-like structures in the data.

While both tests are statistically independent from the DC result under the zero hypothesis, it can be shown that one has to expect a significance of the variability of $\approx 1.5 \cdot \langle S_{\text{DC pearl}} \rangle$ for both tests if a source of sporadic activity is present and the duty cycle of it is sufficiently small (Prahl 1999a, Prahl 1999b).

The reasoning above leads to the conclusion that there might exist a few positions in the sky with moderate DC significances which could exhibit a clear signal from one of the variability tests, therefore DC-selected SGDs with significances $S_{\text{DC pearl}} > 3.5\,\sigma$ are tested with both methods. The resulting significance distributions of S_{kolmog} and S_{exp}, together with a fitted Gaussian, are shown in Fig. 4:

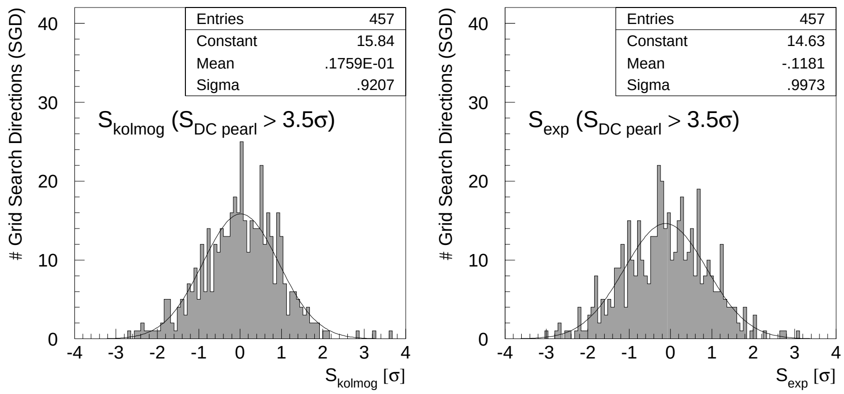

Figure 4: *The obtained spectra for the significances S_{kolmog} (left) and S_{exp} (right) of the two tests on variability. The entering 457 search grid directions are DC-selected from the condition $S_{DC\,pearl} > 3.5\,\sigma$. The curve represents the fitted Gaussian to the distributions.*

It is seen that there are no noticeable deviations from the expectation of a standard normal distribution. The highest significance obtained here is a value of $S_{\text{kolmog}} = 3.67\,\sigma$ for a SGD at $\alpha = 330.2°$, $\delta = 23.3°$, for which the chance probability can be estimated to be 5.8 % under the conservative assumption of all 457 selected SGDs being independent. (The two further results of the Kolmogorov test above $2.5\,\sigma$ belong to neighbouring SGDs.) Therefore one has to conclude that no significant hints for highly variable γ-ray fluxes (corresponding to DC levels of the order of $5 \cdot 10^{-13}$ cm^{-2}s^{-1} at 20 TeV) have been found.

6 Conclusions

In the search for unknown γ-ray point sources in 37 % of the celestial sphere no significant effects of sources are observed. Instead, global upper limits on the γ-ray flux of approximately $8 \cdot 10^{-13}$ cm^{-2}s^{-1} at energy thresholds of typically 20 TeV are derived. These are the first limits of this kind so far in that energy regime. An additional test on variable fluxes yielded no significant hints on variable sources either.

7 Acknowledgements

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