Anisotropies of Cosmic Rays and Search for Intergalactic Cascades from the direction of the Highest Energetic Cosmic Ray Events with the HEGRA Scintillator Array

D. Horns and D. Schmele for the HEGRA Collaboration
II. Inst. f. Exp.Physik, Universität Hamburg, D-22761 Hamburg, Germany

Abstract

Data taken with the HEGRA Scintillator Array within 2.5 years have been used to search for spatial anisotropies in the arrival directions of cosmic rays (E > 20 TeV). For this purpose partial sky survey maps are produced, carefully taking the detector response and changing conditions in the atmosphere into account. In this paper, results on the search for TeV γ–emission correlated with the Galactic Plane and the Gould Belt, a local Galactic region with an enhanced concentration of young bright stars, molecular and dust clouds, are presented. The upper limit for the emission from the Galactic disc of $\Phi_{\gamma}/\Phi_{CR} \approx 10^{-4}$ for $|b_g| \leq 5^\circ$ ($b_g$ denoting the Galactic latitude) and $E > 42$ TeV imposes constraints on the extrapolation of the γ-ray flux measured by EGRET. Furthermore, a search for extended TeV γ–emission correlated with the arrival directions of the cosmic rays with energies well beyond the Greisen-Zatsepin-Kuzmin cutoff has been performed. For this purpose, the directions of 10 events with energies beyond $5 \cdot 10^{19}$ eV including the events belonging to three AGASA clusters and the most energetic event ($E = 320$ EeV) detected by the Fly’s eye detector have been examined for correlated TeV emission. Such a correlation can be expected from sufficiently high energetic nuclei inducing electromagnetic cascades on the diffuse intergalactic (2.7 K) background radiation, eventually producing TeV photons. Interestingly, the direction of the most energetic event yields the highest excess with a chance probability of 1.8%.

1 Introduction

Charged cosmic rays of $E \lesssim 10^{16}$ eV are repeatedly deflected in the $\approx \mu$G magnetic field of the Galaxy causing a diffusive transport. An observer within the Galaxy is expected to observe essentially an isotropic distribution of arrival directions. Anisotropies of small amplitude in the arrival directions of cosmic ray on earth are expected due to the earth movement relative to an isotropic cosmic ray flux (Compton–Getting effect) or possible nearby sources or local magnetic fields. The search for a sidereal dipolmoment has been carried out using the same data set but is not presented here.

Furthermore, and this is the topic of this paper, anisotropies in the arrival directions of air showers may be caused by photons. These photons may be produced in collisions of charged cosmic rays with nuclei of the interstellar medium, producing $\pi^0$ which subsequently decay into energetic photons. The flux of photons from $\pi^0$ production is proportional to the density of cosmic rays and of interstellar matter, which is strongly concentrated towards the Galactic disc. The EGRET experiment on board the Compton Gamma Ray Observatory has measured gamma-ray emission from the Galactic disk in the energy range from 100 MeV to 50 GeV (Hunter et al. 1997). For higher energies, no diffuse emission has been detected so far.

Another possible production mechanism of TeV photons is associated with the propagation of ultra high energy cosmic rays (UHECR) in the Cosmic Microwave Background (CMB) radiation. An UHECR proton beyond the GZK cutoff ($E > 5 \cdot 10^{19}$ eV) propagating through the extragalactic space suffers energy loss in inelastic collisions with photons of the CMB radiation. A variety of inelastic processes channel energy into electromagnetic cascades driven by repeated Compton scattering and pair production processes with the CMB radiation. Once the energy of the photons drops below the pair production threshold energy, no more absorption occurs. As a possible consequence any sufficiently high energetic particle is accompanied by a large number of photons with energies below $\approx 10^{14}$ eV. In case of a steady state injection mechanism and a low ($< 10^{-9}$G) extragalactic magnetic field, the cascade photons would be numerous and the arrival direction would be well associated with the direction of the UHECR.
2 Experimental setup and data selection

The HEGRA Scintillator Array is part of the multi-component Air Shower Detector located on the Canary Island of La Palma (28.8°N 17.9°W, 2200 m a.s.l.). The angular resolution is estimated to be less than 1° and the threshold for air showers of vertical incidence is 20 TeV for photons. The energy threshold for photon induced showers increases to ≈ 1 PeV for showers with a zenith angle of 60°. Details on the performance of the scintillator array can be found in Krawczynski et al. 1996.

The data has been selected carefully from the data taking period November 1993 – June 1996 by monitoring all available properties of the detector performance. Altogether $4.5 \cdot 10^8$ showers (constituting 80% of the data taken in this time period) have been used for this analysis.

The better accuracy in angular resolution obtained with the wide angle Cherenkov Counter array AIROBICC does not improve the sensitivity for extended source regions and for the benefit of a homogenous detector setup, data taken simultaneously with AIROBICC have been excluded from this analysis. A partial sky survey for point sources with AIROBICC data will be presented in a separate contribution (Goetting et al. 1999).

3 Data Analysis

A crucial task in the search for large scale anisotropies is to determine an experimental expectation for an isotropic distribution of cosmic ray arrival directions to be used as background. This Background Map is to be compared with the actual distribution of cosmic ray arrival directions. Since there is no separate and independent measurement of the background available, one has to rely upon methods modeling the background from the data itself.

Conventional methods (see e.g. Alexandreas et al. 1993) could not be applied because of the fact that the time dependence in the detection rate $R = R(t, \theta, \phi)$ ($\theta, \phi$ denoting local coordinates) can not be factorized for the HEGRA data. Instead, it was found to be necessary to describe the rate by the following function (Schmele 1998):

$$R = R(t, \theta, \phi) = R(\theta, \phi) \cdot \exp \left( \frac{P_0 - P(t)}{\Lambda \cdot \cos(\theta)} \right)$$

The values of $\Lambda = 105.4$ g/cm$^2$ and $P_0 = 774.0$ g/cm$^2$ were determined from the data. $P(t)$ denotes the measured air pressure at a given time.

By this empirical function, the 2-dimensional shape of the detection rate $R(\theta, \phi)$ is modified depending upon the air pressure and the zenith angle. The method to determine a Background Map in celestial coordinates can be split roughly into three steps:

1. **Sensitivity Map:** Fill all events in a map of local coordinates: $R(\theta, \phi)$

2. **Measurement Condition Map:** Fill all events in a 2-dimensional map of sidereal daytime and air pressure ($t_{sid}, P$).

3. **Background Map:** Calculate for each bin of the Measurement Condition Map a weighted Sensitivity Map using the overall Sensitivity Map modified by the empirical correction given above and transform this map in celestial coordinates.

The weights used in the last step are taken from the number of entries in each bin of the Measurement Condition Map. The normalization is chosen to ensure that the sum over all bins of the Background Map is equal to the sum over all bins in the Data Map. Since the observation period spans 2.5 years, all contributions by possible sources will be smeared out in the Background Map. The Data and the Background Map contain square bins of $0.1° \times 0.1°$ in celestial coordinates.

On the basis of the Data and the Background Map, searches can be performed on different angular scales. For this purpose, the search bin size has been varied from $1°$ to $10°$. The smallest bin corresponds to a search for point sources, since the angular resolution of the detector is approximately $1°$. To obtain a probability for
4 Results on Anisotropies

We report in this paper on the results from searches for emission from the Galactic plane and the Gould Belt. The results of searches for extended emission from other large scale structures can be found in (Schmele 1998).

4.1 Galactic Plane  So far, the modeling of the EGRET data does not account completely for the flux above 100 MeV (Hunter et al. 1997). The search for emission at even higher energies (above 20 TeV with the HEGRA detector) could help constrain the underlying production mechanisms. The search bin size has been chosen to be 10°. This is in accordance with the emission region measured by EGRET. The upper limit on the relative content of emission from the Galactic plane for $|b| \leq 5^\circ$, $0^\circ \leq l_g \leq 255^\circ$ ($b_g$ and $l_g$ denoting galactic latitude and longitude respectively) and $E > 42$ TeV is $\Phi_\gamma/\Phi_{CR} < 1.6 \cdot 10^{-4}$. This upper limit is about a factor two above the predicted $\gamma$-flux due to nucleon-nucleon interactions. Compared with the extrapolation of the EGRET flux at the considered part of the Galactic disk, the upper limit constrains the integral spectral index for energies above 50 GeV to be steeper than 1.3 (under the assumption of a pure power law spectrum).

4.2 Gould Belt  The population of young stars (spectral class O and B) is concentrated towards the Galactic plane. The subgroup of stars that are within one 1kpc of the solar system is aligned along a plane inclined by 18° against the Galactic plane, named Gould Belt, containing also several molecular and dust clouds (Taylor et al. 1987). Again the search bin size has been chosen to be 10°. The significance for the deviation from an isotropic background in this plane is $3.1 \sigma$. An unconstrained search for the equatorial plane with the highest significance is given

$$b_X = 0^\circ + (30 \pm 5)^\circ \cdot \sin(l - (340 \pm 5)^\circ)$$

yielding $5.9 \sigma$. So far, to our knowledge no motivation for an emission from this plane exists.

5 Search for Intergalactic Cascades

The energy dissipated by UHECR beyond the GZK cutoff in inelastic scattering is partially channeled into electromagnetic cascades driven by inverse Compton scattering and repeated pair production. Once the photons produced are below the threshold for pair production with the CMB photons they are observable at energies below $\approx 100$ TeV. The lower energy bound of observable photons depends crucially on the magnitude of the magnetic field strengths. Synchrotron energy loss is a concurrent energy loss mechanism to inverse Compton scattering and scattering on magnetic fields could weaken a directional correlation with decreasing energy. Detailed simulations of the cascading process are presented elsewhere in these proceedings (Horns 1999). We have searched for directional correlations with the most energetic event detected by the Fly’s Eye Group (Bird et al. 1995) with an energy of $3.2 \cdot 10^{20}$ eV (in the following FE320) and the events belonging to three of the so called AGASA Clusters (Hayashida et al. 1996). The position yielding the most significant excess is the direction of the FE320 event.

Since the directional correlation of the secondary particles can be weakened by the presence of magnetic fields, we have inspected a $30^\circ \cdot 30^\circ$ Field of View centered upon the FE320 direction and have
searched all positions on a 0.1° spaced grid with different search bin radii, ranging from 1° to 5° incremented by 0.25° steps. The largest excess was found at a position shifted by 1° in R.A. from the reconstructed FE320 direction and with a search bin radius of 2.75°. In Figure 1 is a part of the search region displayed, also showing the directional uncertainty of this individual event as given in Bird et al. 1995. Using Monte Carlo generated maps and repeating the search, a chance probability of finding such an excess with a search bin radius > 2.75° has been estimated to be less than 1.8%.

Under the hypothesis of a signal correlated with the source of the FE320 event being an extragalactic steady-state proton accelerator, it is interesting to note, that the ratio of the energy flux of the cascade photons and the energy flux associated with the FE320 event yields a source distance of less than 28 Mpc.

6 Conclusions

We have reported on results obtained with 2.5 years of data taken with the HEGRA Scintillator Array. Selected results on searches for TeV emission correlated with the Galactic Disk and the Gould Belt have been presented. The upper limit on relative abundance of photons arriving from the Galactic Plane $\Phi_\gamma/\Phi_{CR} \leq 1.6 \cdot 10^{-4}$ ($E \geq 42$ TeV, $|b| \leq 5°$) restricts the extrapolation of the EGRET integral Flux measured at GeV Energies to be steeper than a power law with an index of 1.3.

The projection along the Gould Belt yields a significance of 3.1 $\sigma$. The projection with the maximum significance is not associated with any known enhanced matter density or prominent emission feature in other wavelengths.

The search for correlations with possibly extragalactic cascades initiated by 10 selected UHECR events yielded the highest significance in association with the direction of the FE320 event. The chance probability of finding such an excess has been estimated to be < 1.8%. Further studies with the HEGRA Cherenkov Telescope System are underway.

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