Searching for PeV gamma rays with IceCube

THE ICECUBE COLLABORATION[1]
[1]*See special section in these proceedings*

Abstract: IceCube and its surface array IceTop can be used to search for PeV gamma rays. At this energy, pair production on the cosmic microwave background limits the gamma ray horizon to a few tens of kiloparsecs. Therefore, the gamma rays have to originate from within the Galaxy, either from the sites of very energetic accelerators or from the interstellar medium and dense molecular clouds, which act as a target for the local cosmic ray flux.

IceCube can efficiently distinguish PeV gamma rays from the background of cosmic rays. For showers within a limited zenith angle range, the in-ice component of IceCube can detect the Cherenkov radiation released by muons that penetrate kilometers deep into the ice while the surface component, IceTop, can measure particles from the same air shower. Gamma-ray air showers have a much lower muon content than cosmic ray air showers of the same energy. IceTop can be used to search for gamma-rays by selecting those showers that lack a signal from a muon bundle in the deep ice.

We investigate the possibility of detecting gamma-ray air showers with IceCube and present results of one year of data, taken in the 2008/2009 season when the detector consisted of 40 strings and 40 surface stations. We derive an upper limit on the ratio of gamma showers to cosmic rays showers of $8.1{\cdot}10^{-4}$ above 1.2 PeV in a region of 10 degrees around the visible part of the Galactic plane. The projected gamma-ray sensitivity of full IceCube, completed at the end of last year, is also studied.

Corresponding author: Stijn Buitink[2,3] (*sbuitink@vub.ac.be*)
[2]*Lawrence Berkeley National Laboratory, Berkeley, USA*
[3]*Interuniversity Institute for High Energy, Vrije Universiteit Brussel, Belgium*

DOI: 10.7529/ICRC2011/V01/0939

Keywords: Gamma Rays; Galactic Accelerators; Extended Air Showers; IceCube; IceTop

1 Introduction

Gamma rays are an important tool for studying the cosmos; unlike cosmic-rays (CRs), they point back to their points of origin. Air Cherenkov telescopes have detected many high-energy ($E > 1$ TeV) gamma-ray sources. Within our galaxy, gamma-rays have been observed coming from several types of sources: supernova remnants, pulsar wind nebulae, binary systems, and the Galactic center. Extra-galactic sources include Active Galactic Nuclei (AGNs), and other objects containing supermassive black holes. Surface air shower arrays like Milagro have performed all-sky searches for TeV gamma-rays. Although these detectors are less sensitive to point sources than Air Cherenkov telescopes, they have identified several diffuse sources [1].

At higher energies, extra-galactic sources are unlikely to be visible, because more energetic photons are likely to interact with cosmic microwave background radiation (CMBR) photons, and infrared starlight from early galaxies, producing e^+e^- pairs. At 1 PeV, for example, near the peak of the cross-section, photons are limited to a range of about 25 kiloparsecs. It is unknown whether Galactic accelerators exist that can produce gamma rays of such high energy, but an expected flux results from the interaction of CRs with the interstellar medium (ISM).

To date, the best statistics on photons with energies above about 300 TeV come from CASA-MIA, which has set a limit on the fraction of photons in the cosmic-ray flux of 10^{-4}, at energies above 600 TeV [2]. They also set a limit on the relative flux of photons coming from within 5° of the galactic disk of less than 2.4×10^{-5} [3]. This is close to the theoretical expectation due to CR interactions with the ISM. For a Northern hemisphere site like CASA-MIA, the average theoretical prediction is 2×10^{-5} [4]. At somewhat lower energies, gamma-ray emission from the Galactic plane may already have been seen [5].

2 Detection Principle

We select a sample of air showers that are successfully reconstructed by IceTop and have a shower axis that passes through the instrumented area of IceCube deep in the ice. Investigating the muon component of the air showers in the ice allows for CR composition studies. In this analysis, we create a sample of gamma-ray candidates by selecting

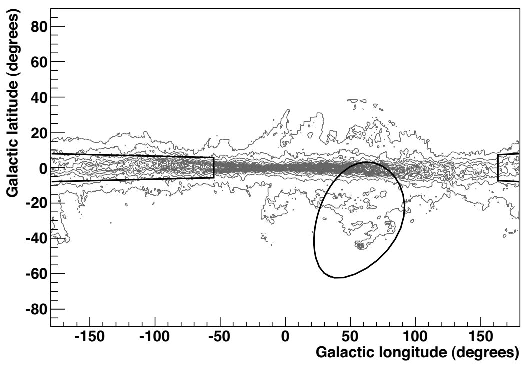

Figure 1: Gamma-ray field of view for IceTop/IceCube in Galactic Coordinates (black circle). The rectangular area is the region for which CASA-MIA [3] has set upper limits on the Galactic diffuse photon flux. The part of the Galactic Plane covered by IceCube is smaller but closer to the Galactic Center.

only those air showers which do not produce any signal in the deep ice. The energy threshold of the air showers must be chosen sufficiently high to reduce the background of muon-poor CR showers. At 1 PeV, less than 0.1% of all proton showers do not contain muons with an energy over 500 GeV, which is approximately needed to reach IceCube when traveling vertically. However, only 16% of all gamma-ray showers will produce a signal in IceCube at that energy. At lower energies, the CR background becomes too large to find a possible gamma-ray signal. Moreover, the shower size becomes to small to trigger a sufficient amount of IceTop tanks for high quality angular reconstruction.

The requirement of IceTop-IceCube coincidence confines the maximum zenith angle to $\sim$30 degrees. Since IceCube is located on the geographic South Pole, this means that our Field of View (FOV) is constrained roughly to the declination range of -60 to -90 degrees, which includes part of the Galactic Plane (see Fig. 1). The Magellanic clouds also lie within the FOV, but at distance of $\sim$50 kpc, a possible gamma-ray flux at $\sim$1 PeV from the Large Magellanic Cloud is reduced by a factor $\sim$100.

Within our candidate sample we search for a local increase in the flux from a point source or the Galactic Plane. We make use of the unique geographical position of IceCube: as the Earth rotates the declination remains a fixed function of the zenith angle, while the Right Ascension (RA) rotates with respect to the azimuth angle. A diffuse flux of CR showers therefore produces a flat distribution in RA (whereas the azimuth distribution is a complex function of the detector shape). Therefore, a clustering of events in RA can be attributed to a gamma-ray component in the flux.

3 IC40 Analysis

Between April 1 2008 and June 1 2009, IceCube has taken data with a configuration of 40 strings and 40 surface stations (IC40). There are several trigger conditions based on different signal topologies. For this analysis we use the 8 station surface trigger, which requires a signal above threshold in both tanks of at least 8 IceTop stations. Although an additional signal in IceCube is not required for this trigger, hits in the deep detector within a time window of 10 μs before and after the surface trigger are stored.

The air shower parameters are reconstructed with a series of likelihood maximization methods [7]. The arrival direction is determined with a resolution of $1.5°$.

In the selection of photon shower candidates from the data sample we distinguish two steps: level three (L3) and level four (L4). At L3, two parameters are used to constrain the geometry and ensure the shower axis passes through the instrumented volume of IceCube. The IceTop containment parameter $C_{\rm IT}$ is a measure of how centralized the core location is in IceTop. $C_{\rm IT} = x$ means that the core would have been on the edge of the array if the array would be x times its actual size. The string distance parameter $d_{\rm str}$ is the distance between the point where the shower reaches the depth of the first level of DOMs and the closest inner string. Inner string, in this sense, means a string which is not on the border of the IC40 configuration. IC40 contains 17 inner strings. The complete set of L3 cuts is composed of these geometrical parameters, the reconstructed shower energy $E_{\rm min}$, and reconstruction quality parameters. The L4 stage imposes only one extra criterion to the event: there should be no hits in IceCube.

Simulations show that 16% of the gamma-ray showers is excluded by the L4 cut. The amount of CR showers still present at L4 is not simulated. Instead, this value is determined from data, where it is assumed that CRs dominate the sample in the off-source region (i.e. away from the Galactic Plane).

3.1 Galactic Plane Test

The IC40 data set consists of 368 days of combined IceCube/IceTop measurements. The data from August is used as a burn sample, which means that it is used to tune the parameters of the analysis, and then discarded. The remaining data is used for the actual analysis.The cut parameters of this analysis were optimized to maximize the chance for discovery, because the potential of this analysis to constrain the gamma ray flux would not be competitive with already existing limits. A discovery above existing limits is in principle possible, since our FOV covers a part of the Galactic Plane not seen by previous searches, close to the Galactic center.

There are three cut parameters that are optimized by using the burn sample: $E_{\rm min}$, $C_{\rm IT}$ and $d_{\rm str}$. This is done by scanning through all combinations of parameters within a certain range: 600 TeV$< E_{\rm min} <$ 2 PeV in steps of 100 TeV,

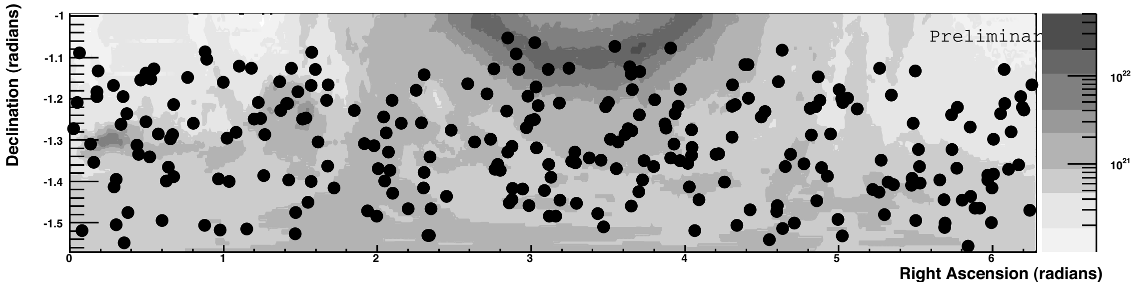

Figure 2: The 268 candidate gamma-ray events superimposed on HI column densities based on [6]

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$0.5 < C_{\mathrm{IT}} < 1.0$ in steps of 0.1 and 50 m $< d_{\mathrm{str}} < 90$ in steps of 10 m. For each combination the number of events N_S is counted which are located in the source region, defined as within 10 degrees of the Galactic Plane. Then, the events are scrambled multiple times by randomizing the RA of each data point. The quality of the combination of cut parameters is given by the fraction of scrambled data sets that produce the same or higher amount of events in the source region as the original data set. The combination $E_{\mathrm{min}} > 1.4$ PeV, C_{IT} <0.8 and $d_{\mathrm{str}} < 60$ m gives the best correlation with the Galactic Plane. Because of the small size of the burn sample, this correlation is most likely accidental.

The optimized cuts are applied to the complete IC40 data set minus the burn sample. There are 268 candidate events of which 28 are located in the source region. Fig. 2 is a map of the sky showing all 268 events. The colors in the background are the integrated neutral atomic hydrogen (HI) column densities based on data from the Leiden/Argentine/Bonn survey [6]. These values have no impact on the analysis and are only plotted to indicate the positions of the Galactic Plane and the Magellanic Clouds. The significance of the correlation with the Galactic Plane is again tested by producing data sets with scrambled RA. An equal or higher number of source region events is found in 21% of the scrambled data sets. The source region has a non-significant upward fluctuation of +0.9σ.

We follow the procedure of Feldman and Cousins [8] to construct an upper limit on the ratio of gamma rays to CRs. The background is determined by selecting a range of RA that avoids the source region. Within this range the data points are scrambled multiple times and for each scrambled set the number of events in a pre-defined region of the same shape and size as the source region is counted. This yields a mean background of 24.13 events for the source region. To derive at an upper limit on the ratio between the flux of gamma rays to CR several quantities have to be included which have been found with MC studies. The energy reconstruction of IceTop is calibrated on proton showers and overestimates the gamma-ray shower energy by 14%. The lower energy limit of 1.4 PeV on CR showers corresponds to 1.21 PeV gamma-ray showers. Other quantities that have been found with simulation are the fraction of gamma-ray showers producing a muon signal in IceCube, and the difference in the effective area for CR and gamma ray showers. Finally we arrive at a 90% C.L. upper limit on the ratio of gamma-to-CR shower above 1.21 PeV of $8.1 \cdot 10^{-4}$, plotted in Fig. 3.

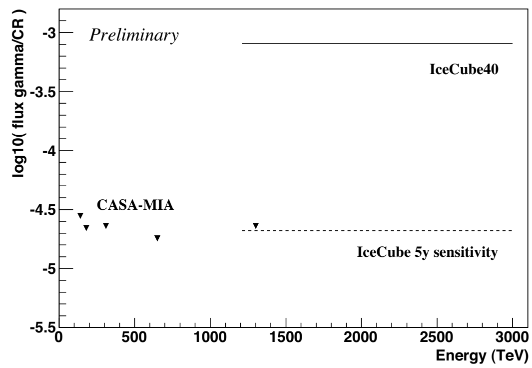

Figure 3: Limits on the gamma-ray to CR flux ratio from within 10 degrees of the Galactic Plane by CASA-MIA [3] and IC40 analysis. The sensitivity of 5 years full IceCube data is indicated by the dashed line.

3.2 Unbinned point source search

In an additional search for point-like sources we account for the possibility that a single source dominates the PeV gamma ray sky and that this source does not necessarily lie close to the Galactic Plane. An unbinned point source search is performed on the sky within the declination range of -80° to -60° in a method that follows [9].

The data is described by an unknown amount of signal events on top of a flat distribution of background events. In an unbinned search, a dense grid of points in the sky is scanned. For each point a maximum likelihood fit is done for the relative contribution of source events over background events.

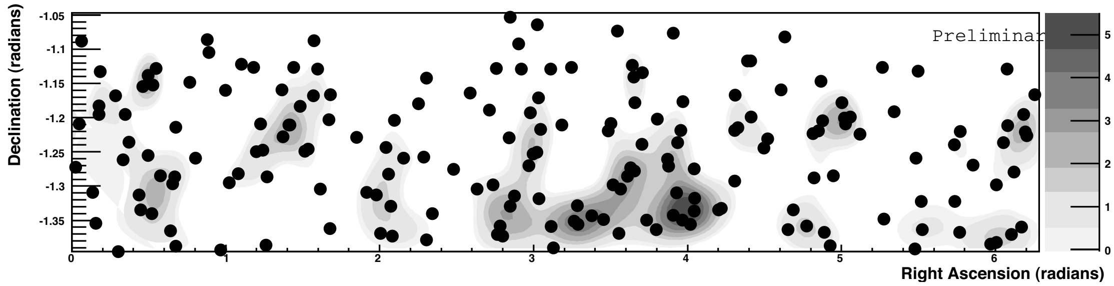

Figure 4: Lambda contours of an unbinned search for gamma-ray point sources.

For a particular event i in a sample of N events, the probability density function (PDF) is given by

$$P_i(n_S) = \frac{n_S}{N} S_i + \left(1 - \frac{n_S}{N}\right) B_i \quad (1)$$

where n_S is the number of events that is associated to the source, B_i is a flat background PDF, and

$$S_i = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{\Delta\Psi^2}{2\sigma^2}\right) \quad (2)$$

is the two-dimensional Gaussian source PDF, in which $\Delta\Psi$ is the space angle between the event and the source test location, and $\sigma = 1.5°$ is the angular resolution of IceTop. For each point in the sky there is a likelihood function

$$L(n_S) = \Pi_i P_i(n_S), \quad (3)$$

and associated test statistic

$$\lambda = -2\left(\log(L(0) - L(n_S))\right), \quad (4)$$

which is optimized for n_S.

Fig. 4 is a map of the sky within range of -80° to -60° showing the events in this region and contours of the test statistic λ. The maximum value is $\lambda = 5.5$ at $\delta = -1.34$ and RA= 3.99, corresponding to 7.25 signal events. The significance of this value for λ is found by producing $10,000$ scrambled data sets by randomizing the RA of each data point. The mean test statistic value for the hottest spot is $\lambda = 5.74$, so the actual data set has a slight underfluctuation of -0.1σ and is fully consistent with a flat background. A 3σ upward fluctuation would have corresponded with $\lambda = 12.5$.

An upper limit on the gamma-ray flux from point sources can be set by assuming all 7.25 events associated to the hottest spot are actual gamma-rays from a point source. The effective area of IC40 for a source at a zenith angle of 13.2° is $5.7 \cdot 10^4$ m^2 and the total observation time is $3.2 \cdot 10^7$ s. Assuming an spectrum with index $\gamma = -2$ an upper limit of $7.0 \cdot 10^{-19}$ cm^{-2}s^{-1}TeV^{-1} at $E = 1.2$ PeV can be placed with a C.L. of 99%.

4 Full IceCube sensitivity

The construction of IceCube was finished in the winter of 2010/11. With a larger array the acceptance increases considerably. Because of the condition that the shower axis has to be inside the instrumented area of both IceCube and IceTop, the increase is especially dramatic at higher zenith angles. The maximum zenith angle is also larger, which extends the FOV to cover a larger part of the Galactic Plane and probe an area even closer to the Galactic Center. Additional efficiency is gained by using the information of isolated hits. In the IC40 configuration, hit information was only available when neighboring DOMs both detected a signal, while isolated hits were discarded. The isolated hit information will increase the discriminating power between CRs and gamma-rays. Furthermore, progress in shower core reconstruction algorithms have reduced the number of mis-reconstructed showers. The expected sensitivity of 5 years of IceCube data is plotted in Fig. 3.

5 Conclusion

We have investigated the sensitivity of IceCube for the detection of PeV gamma-rays from the Galactic plane. With one year of data from the unfinished detector we have derived a limit on the flux of gamma rays to CR which is not competitive with existing limits. The full IceCube detector will be able to reach a sensitivity to the diffuse Galactic flux similar to that of CASA-MIA, for slightly higher energies.

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