Nuclear Instruments and Methods in Physics Research A 851 (2017) 125–131

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Sensitivity estimate of the MACE gamma ray telescope

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ARTICLE INFO

Keywords:
Cherenkov telescopes
Cosmic rays
Gamma rays
Classification
Random forest
IACT

ABSTRACT

The MACE (Major Atmospheric Cherenkov Experiment) is a 21 m diameter γ-ray telescope which is presently being installed at Hanle in Ladakh, India (32° 46′ 46″ N, 78° 58′ 35″ E) at an altitude of 4270 m a.s.l. Once operational, it will become the highest altitude very high energy (VHE) γ-ray telescope in the world based on Imaging Atmospheric Cherenkov Technique (IACT). In the present work, we discuss the sensitivity estimate of the MACE telescope by using a substantially large Monte Carlo simulation database at 5° zenith angle. The sensitivity of MACE telescope is estimated by carrying out the γ-hadron segregation using the Random Forest method. It is estimated that the MACE telescope will have an analysis energy threshold of 38 GeV for image intensities above 50 photoelectrons. The integral sensitivity for point like sources with Crab Nebula-like spectrum above 38 GeV is ~2.7% of Crab Nebula flux at 5 σ statistical significance level in 50 h of observation.

1. Introduction

Among the various fields of astronomy (Radio, Infrared, Optical, Ultraviolet, X-rays, γ-rays, gravitational waves), ground based γ-ray astronomy is one of the youngest entrants. This field was pioneered by the Whipple group who made the first unambiguous detection of TeV γ-rays from the Crab Nebula in the year 1989 [1]. Subsequently, over the next decade, γ-rays were detected from various astrophysical sources [2]. This field has seen remarkable progress in recent years with the source count increasing from just a single source in 1989 to 175 confirmed TeV γ-ray sources[1] as of now. Imaging Atmospheric Cherenkov Technique (IACT) is based on detecting the Cherenkov radiation generated by the cosmic γ-rays when they enter the Earth's atmosphere. Presently three major operational IACT based telescopes are MAGIC [3], HESS [4] and VERITAS [5]. The MAGIC telescope consists of two 17 m diameter telescopes at the Canary island of La Palma. The analysis energy threshold of MAGIC is ~80 GeV. The VERITAS telescope is an array of four 12 m diameter telescopes at southern Arizona, USA. It has an analysis energy threshold of ~135 GeV [6]. HESS telescope, situated in Namibia, is a mixed array consisting of four 12 m telescopes, named as HESS-I and one 28 m large size telescope, named as HESS-II. HESS-I alone operates at an analysis energy threshold of ~158 GeV [7] whereas the preliminary simulation studies show that HESS-II has an analysis energy threshold of ~50 GeV [8]. In order to augment the capability of IACT based telescopes in few GeV to few TeV energy range, an international consortium of worldwide researchers are setting up an open observatory known as the Cherenkov Telescope Array (CTA) [9]. CTA will consist of two large arrays of IACT based telescopes, one in the Northern Hemisphere with an emphasis to study extragalactic objects and a second array in the Southern Hemisphere to concentrate on galactic sources. The Southern array which is being set up first will deploy telescopes of various diameters to cater to the wide energy range of few tens of GeV to few tens of TeV. A compact array of 4×23 m diameter telescopes will cater to the lower end of energy range.

In the same endeavour, a new Indian initiative in gamma-ray astronomy, the Himalayan Gamma Ray Observatory (HIGRO), is setting up an IACT based telescope known as the **MACE** (**M**ajor **A**tmospheric **C**herenkov **E**xperiment) at Hanle in the Ladakh region of northern India. MACE, presently being set up at an altitude of 4270 m, is a 21 m diameter telescope with a total light collector area of ~337 m^2 with effective focal length of ~25 m. Compared to the high altitude of MACE telescope, MAGIC, HESS and VERITAS telescopes are operational at an altitude of 2225 m, 1800 m and 1275 m respectively. The idea of an IACT based telescope at high altitude (5 km) was introduced by Aharonian et al. [10]. They discussed the concept of a stereoscopic array of several large imaging atmospheric Cherenkov telescopes having an energy threshold of 5 GeV. Although it should be noted that they discussed about a stereo array, whereas MACE is a standalone single telescope. The stereoscopic approach has many advantages

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http://dx.doi.org/10.1016/j.nima.2017.01.005
Received 4 March 2016; Received in revised form 3 January 2017; Accepted 3 January 2017
Available online 05 January 2017

compared to the stand alone IACT. This approach allows unambiguous reconstruction of shower parameters. It also leads to effective suppression of night sky background and muon background because of the reduction in the random coincidences, leading to reduced pixel trigger threshold and hence lower energy threshold. In addition to it, the hadronic showers are rejected more efficiently compared to a single IACT based telescope on shape cuts in multiple views. The simultaneous observation of air shower by stereoscopic telescope, compared to a single telescope, leads to improved shower direction reconstruction as well as core location. The main advantage of having a stereoscopic array of 20 m diameter telescope at an altitude of 5 km is very low γ ray energy threshold ~5 GeV on account of less absorption of Cherenkov photon, as well due to geometric effect on account of higher altitude leading to higher photon density.

In the present work, we will discuss the preliminary sensitivity estimate of the MACE telescope. This study is organized as follows. In Section 2, we will introduce the MACE telescope. In Section 3, we will discuss the generation of Monte Carlo simulation database along with the technique used in the field of IACT. Section 4 will discuss the Random Forest method. In Section 5, we will define the Integral sensitivity and its estimation. Results and discussion will be presented in Section 6. Finally we will conclude the study along with the planned future studies.

2. The MACE telescope

The MACE is an Indian effort to set up a very high energy (VHE) γ-ray IACT based telescope. The MACE telescope is presently being installed at Hanle in Ladakh, India (32° 46′ 46″ N, 78° 58′ 35″ E) at an altitude of 4270 m a.s.l. It is a 21 m diameter telescope which will deploy a photomultiplier tube (PMT) based imaging camera consisting of 1088 pixels. The diameter of each PMT is 38 mm with angular resolution of 0.125° and an optical field of view of the full camera ~3.5° × 4°. In order to reduce the dead space between the PMTs, a light concentrator having a hexagonal entry aperture of 55 mm and a circular exit aperture of 32 mm is placed on top of the PMTs. The imaging camera of MACE telescope has been designed in a modular manner consisting of 68 modules of 16 channels each. The MACE camera layout has been shown in Fig. 1. The detailed trigger scheme is described in [11]. Out of 1088 pixels, the innermost 576 pixels (24×24) will be used for trigger generation. The trigger field of view is ~2.6° × 3°. Conventionally, the event trigger in an Atmospheric Cherekov Telescope is generated by demanding a fast coincidence between few PMTs, generally 2–6. Since the γ-ray images are more compact compared to the background events, the chance coincidence rate can be reduced by limiting the n-fold topological combination of pixels. The MACE telescope uses nearest neighbour close cluster patterns. It has an option of using various programmable trigger configuration such as 2 CCNN (close cluster nearest neighbour pairs), 3 CCNN (close cluster nearest neighbour triplets), 4 CCNN (close cluster nearest neighbour quadruplets). Here CCNN is defined as the pattern in which if any one of the fired pixels is removed, the remaining pixels should be still adjacent. MACE trigger will be generated in two stages: In the first stage a m-fold coincidence in a module between nearest neighbour pixels with a coincidence gate width of 5 ns is demanded. In the second stage, partial triggers from individual modules are collated so that events, spread over adjacent modules (2, 3 or 4) satisfying the chosen multiplicity condition generate the trigger. The MACE camera layout with 3, 4 and 5 CCNN trigger patterns is shown in Fig. 1.

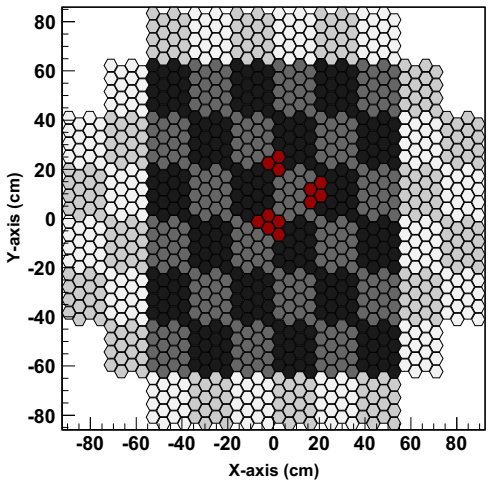

Fig. 1. The MACE camera layout showing a total of 1088 pixels divided into 68 modules with 16 PMT each. The trigger is generated from the darker shaded area consisting of 576 pixels. Typical trigger pattern of various programmable scheme (3,4,5 CNNN) is shown in red color. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

MACE Telescope will use a quasi-parabolic light collector to image the Cerenkov flash on a PMT camera. The light collector of the telescope will be made of 356 mirror panels of 984 mm×984 mm size fixed at a square pitch of 1008 mm on a paraboloid shape dish. Each panel will consists of four 488 mm×488 mm facets of spherical mirrors made of aluminum with a SiO_2 coating. The total light collector area will be ~337 m^2. The mirror facets have a graded focal length of 25–26.5 m which ensures that the on-axis spot size is minimum at the focal plane.

3. Generation of Monte Carlo simulation database

A Monte Carlo simulation database at 5° zenith angle was generated. The details are as follows:

3.1. Simulation database

The extensive air shower (EAS) library for MACE simulation was generated using a standard air shower simulation package CORSIKA(v6.990). This code is developed at Karlsruhe university and available for use on request. This Monte Carlo method based code simulates the secondary particle cascade generation in the atmosphere as high energy primary particle enters the Earth's atmosphere and undergoes many electromagnetic as well as hadronic interactions. Many models to simulate these interactions are available in this code and the Cerenkov light generation by the relativistic leptons as they zip through the atmosphere is also simulated. For this work, we have used EGS4 model for the electromagnetic interactions. For low energy (upto Ĩ00 GeV) hadronic interactions, we have used GHEISHA model while high energy interactions are modelled using QGSJet-I model. We have used CEFFIC option to incorporate the en-route absorption of Cerenkov photon. We have used US standard atmosphere model supplied with CORSIKA package. The observation level was set to the altitude of the telescope site. The Earth's magnetic field values measured at the Hanle are 31.95 μT for horizontal component along local north direction and 38.49 μT for vertical component in downwards direction. The Cerenkov photons were stored within the wavelength range 240–650 nm as the MACE camera PMTs are sensitive in this range.

Using this setup, we generated EAS library for four primary particles – γ-ray, proton, electron and α particle. The spectral indices used are 2.59 [12] for γ-ray, 2.7 for proton, 3.26 for electron and 2.63 for α particle. Other input parameters which vary with particle type, are listed in Table 1. In this work we focused on estimating the sensitivity of the telescope for on-axis point sources only (view cone angle is maintained at zero value for γ-ray showers). The protons, electrons and alpha particles are simulated diffusively in a certain view cone angles, as described in the Table 1. It evident from this table that we generated more than 34 million γ-ray showers and nearly 1 billion showers for