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Design considerations for MACE and MYSTIQUE telescope systems

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Abstract.
The MACE and the MYSTIQUE telescopes are being set up in India as part of the GRACE (Gamma-ray Astrophysics through Coordinated Experiments) facility. We present here the important design features of these two telescope systems.

1 Introduction

The GRACE is a new astronomical facility being set up in Western India at Mt. Abu, Rajasthan (24.6° N, 72.7° E, 1400 m asl), for high-sensitivity investigations in the gamma-ray spectral band, covering nearly 10 decades of photon energy ($\sim$ 100's keV-100's TeV). Its 4 principal components are the TACTIC, MACE, MYSTIQUE and BEST experimental systems. While the first 3 experiments use the atmospheric Cerenkov technique for detecting single gamma-ray photons in the energy range $\sim$ 10's GeV-100's TeV, the fourth experiment, BEST, will attempt to detect short time-scale gamma-ray bursts in the photon energy range $\sim$ 100's keV to 100's MeV through the atmospheric scintillation technique (Bhat, 2000). Already, the 4-element array of imaging Cerenkov telescopes, TACTIC, has been commissioned at Mt. Abu and 3 source detections have been made with it so far (Bhat et al.,1997, Tickoo et al., 2001). Presently, the design and development work on the MYSTIQUE and MACE telescopes is in progress and, in this paper, we present a status report on these experiments.

2 MYSTIQUE

Keeping in mind the astrophysical importance and the observational challenges in making a source detection in the ultra-high energy photon regime (Ong, 1998), the MYSTIQUE is planned to be the highest sensitivity experiment attempted so far in this spectral band (10's-100's TeV). To successfully realise this design goal, the MYSTIQUE will use an array of 256 wide-angle Cerenkov detector cells which are spaced over a physical area of 600m $\times$ 600m with an inter-cell separation of $\sim$ 40 m. Apart from the associated large effective collection area of the array, another important factor which ensures a high signal (gamma-ray)-to-noise (cosmic ray) ratio at the intrinsic level is the excellent angular resolution ($\sim$ 0.2° diameter) expected from the array right from its effective gamma-ray threshold energy ($\sim$ 10 TeV). Further (significant) enhancement in the gamma-ray flux sensitivity of the experiment is sought by explicitly exploiting the progenitor-particle characterization roles of the lateral distribution of photon density and time-structure of the associated Cerenkov radiation wavefront as well as time-parameters and polarization state of the atmospheric Cerenkov events (Bhat et al, 1999; Rannot et al, 1997). Using all these event 'diagnostic tools', it is expected that the MYSTIQUE can accept gamma-rays at 50-70$\%$ level and reject cosmic-ray background at $\geq$ 99$\%$ level. The implied photon flux sensitivity of the experiment is shown in Fig.1a as a function of the gamma-ray primary energy. Also plotted in the figure are the UHE flux estimates for the Crab Nebula ($\sim$10-300 TeV), based on a recently published work on the synchrotron self-Compton model of the source by de Jager (2000). It is evident that the projected flux sensitivity of the MYSTIQUE is favourably placed upto $\sim$ 200 TeV photon energy with respect to this model estimate. In our calculations, it has been assumed that the gamma-ray fraction accepted is $\sim$ 50-70$\%$ and the photon fraction rejected $\sim$ 99$\%$. The effective area of the array is assumed to be increasing from 3.6$\times$ 10^5 m^2 at 10 TeV to nearly 10 times more at $\sim$ 300 TeV photon. The lay-out planned for each of the 64 modules of the MYSTIQUE array is schematically shown in Fig.1b. Each module consists of 4 detector cells located more or less symmetrically with respect to its data acquisition and recording system. Each detector cell comprises 3 closely-spaced large-area (20 cm diameter) wide-angle (FoV = 45° half-angle) Cerenkov radiation detectors (Photomultiplier tube type ETL 9352 KB) from which signals are taken through short cable lengths (RG8U, $\sim$ 30 m long) to the Module DAQS. Each detector is operated at a

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discrimination level of $\sim 3\sigma$, corresponding to a shot noise-generated single's rate of $\sim$ 50 kHz. A 3-fold prompt coincidence (resolving gate width $<$ 5 ns) is taken to mark the onset of an event. The relative arrival times of the event at the 4 detector cells of each module are logged with a time-resolution of 0.5 ns to derive the event arrival direction with a resolution of $\sim 0.2^\circ$. The temporal profile of the event, as detected by each detector cell, is also recorded with $\sim$ 1ns resolution alongwith the total charge-content of the event. Provision is also made to measure the polarization state (degree and angle of linear polarization vector) of the recorded Cerenkov event near the centre of each module Each MYSTIQUE module is provided with a GPS-slaved precision timing facility for recording the absolute epoch of an event with an accuracy of $\leq 1\ \mu$ s. The data recorded at all the 64 MYSTIQUE modules are pooled together at a central location for first-level analysis and archiving using ethernet connectivity. Radio-isotope-based light pulsers are provided with each detector for on-line, absolute calibration purposes.

3 MACE

It is planned to be a system of 2 high-definition imaging Cerenkov telescopes operated in a stereoscopic mode for gamma - ray astronomy investigations in the sub-TeV energy range (projected gamma-ray threshold energy $\sim$ 20 GeV). Each alt-azimuth mounted telescope (Fig.2a) will use a 17 m diameter, high optical quality metallic mirror (made up of diamond-turned aluminium facets) similar to that used in the MAGIC telescope (Barrio et al, 1998). The overall profile of the light collector will approximate a paraboloid surface comprising concentric rings of mirror facets with a graded focal length. Such a profile is isochronous and also produces a sharp focus. The imaging camera, mounted in the mirror focal-plane, comprises a cluster of 832 photomultiplier tubes (PMT) of two sizes, providing an overall Field of View (FoV) of $4^\circ \times 4^\circ$. The innermost pixels (FoV $2.4^\circ \times 2.4^\circ$), used for generating the event trigger, will have a resolution of 0.1° , while the remaining pixels will have a resolution of 0.2° (Fig.2b) The signal processing electronics and instrumentation is mounted at the back of the mirror of the corresponding telescope in order to retain the relative sharpness of the Cerenkov pulse (duration $\leq$ 10 ns) and thus avoid taking in excessive light of night sky noise, resulting otherwise in a higher effective threshold energy for the MACE. The proposed stereoscopic mode of MACE operation leads to the following important advantages: It effectively suppresses the local muon background, an important constraint on sensitivity in the sub-TeV energy regime; It also helps to preferentially pick up gamma-ray events of a point-source origin and significantly eliminate isotropic backgrounds of cosmic-ray nuclear and electron origins. Furthermore, this mode of operation may lead to a lower effective gamma-ray threshold and a more accurate estimation of the primary energy. Given these design specifications, the MACE promises to be a powerful instrument for gamma-ray source studies in the sub-TeV energy range, including for EGRET-detected pulsars, Supernova remnants, active galaxies and so-far unidentified objects (Thompson et al, 1995). Monitoring for high energy tails in cosmic gamma-ray bursts is another important experimental investigation planned for the MACE. Fig. 2c compares the estimated sensitivity of the MACE with the Crab pulsar spectrum modulated with an exponential tail characterised by an energy cut off value $E_0 \sim 60$ GeV Two values of the on-source observation time (50 hrs and 100 hrs) and the pulsar light-curve duty-cycle (10% and 100%) are considered. Calculated flux value for one medium mass x-ray binary system and experimental upper limits obtained by the Whipple group (Hall et al.,1999) on this system and two radiopulsars are shown for a comparison.

4 GRACE Electronics Modules

With the aim of ensuring a fast time-response, high channel density and low power dissipation, special signal processing electronics modules based on ASIC and hybrid circuits are being developed for the MYSTIQUE and MACE experiments. Each of these modules called GEM (GRACE Electronics Module) can handle signals from a set of 16 photomultiplier channels. As shown in Fig.3 apart from fast amplifiers, programmable discriminators, scalers, anode current monitors and charge digitizers for 16 channels, the GEM has a 486 processor embedded in it. This processor handles all the house keeping jobs and ethernet communication with a network of workstations located in the control room. A 16 channel, first-level trigger (FLT) generator, based on a programmable memory, also forms a part of the GEM. When used with the MYSTIQUE, each GEM will also have a 4 channel TDC incorporated for monitoring the inter detector delay of the Cerenkov events picked up by the 4 detector cells of a module. The data acquired by each GEM module will be temporarily stored in its local memory before being transmitted to the control workstations for analysis and archiving.

5 Implementation Schedule

The design and development activity for both the telescope systems is at an advanced stage. The prototype GEM module, which forms the basic building block of their back end instrumentation, will be ready for field trials by Dec. 2001. The 256 detector MYSTIQUE array is likely to be operational by Dec. 2003 while the first element of the MACE telescope pair is expected to see the first light by Dec. 2005.

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