Extending The Cherenkov Technique Down To An Energy Threshold Of A Few GeV: The Ultimate Instrument For Ground-Based Gamma-Ray Astronomy

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(*) M. Merck gratefully acknowledges support by the German BMBF through grant 05 CM0MG1

Abstract

We investigate the technologies needed to extend the Cherenkov technique to reach the physical limit at which particles in the air-showers emit too few Cherenkov photons to create an image. We present our ideas for the design of such an instrument, with an energy threshold down to ~ 5 GeV, and a sensitivity of $\sim 3 \cdot 10^{-10}$ cm^{-2} s^{-1} above 5 GeV.

1. Introduction

The most sensitive detectors of ground-based gamma-ray astronomy detect the Cherenkov photons emitted by relativistic particles in an air shower initiated by primary gamma rays when impinging on the Earth's atmosphere. Using imaging telescopes the weak gamma-ray signal can be detected over the strong background induced by hadronic showers. In the energy range which was accessible by the previous generation of imaging air Cherenkov telescopes (IACTs) this was achieved using image parameters as introduced by Hillas [5]. The largest IACT is the MAGIC telescope located at La Palma, Canary Islands Spain [1, 7] which is presently becoming operational. It has a 17m diameter mirror and will be capable of detecting air showers originating from primary gamma-rays with energies well below 35 GeV. However, still larger telescopes will be needed to fur-

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ther exploit this technique to lower threshold energies. Showers originating from primary gamma rays of a few GeV still produce enough Cherenkov light to be detectable by sufficiently sensitive telescopes [8]. The fluctuations in the shower development due to the low number of charged particles (electrons/positrons) above Cherenkov threshold in the air shower (some 20 charged particles at primary energies of 5 GeV) finally limit this technique. Remarkably, the background induced by primary hadrons as well as the background from cosmic ray electrons is strongly suppressed below 10 GeV. A key issue to be attacked by the lowest energy threshold IACT is the avoidance of the Stecker-Fazio pair-production cutoff [10] and thus increasing the gamma-ray visible part of the Universe to the highest redshifts [6]. Moreover, indirect dark matter searches in this energy region can provide crucial constraints for supersymetric particles [3]. Building on our experience from MAGIC in reducing the energy threshold of IACTs using large, lightweight, isochronous mirrors we extend the design concept to a new type of telescope which we call ECO-1000 (European Cherenkov Observatory 1000 m^2 Telescope) reaching the lowest possible threshold.

2. Parameters of the ECO-1000 telescope design

The amount of Cherenkov light scales linearly down to a few GeV [8]. Thus, scaling from the MAGIC 17m telescope requires to collect 10 times more photons. This can be achieved by increasing the quantum efficiency and photoelectron collection efficiency of the photon detectors by a factor of 2-2.5 and by increasing the mirror area by a factor of 4 to 1000 m^2 (hence the acronym ECO-1000). New hybrid photo detectors (HPDs) using novel photocathode materials like GaAsP promise increased quantum efficiencies (up to 50%) compared to classical PMTs [2, 4]. A wavelength shifter coating has to be applied to the HPDs entrance window, in order to optimally adopt the spectral sensitivity of the photocathode to the Cherenkov light spectrum strongly peaked in the near UV. The increase in mirror area requires new construction techniques as pioneered by MAGIC, to keep the weight in reasonable limits allowing for fast telescope slews in reaction to GRB alerts. Systematic use of lightweight materials such as carbon fiber and continuous active control of mirror dish deformations keeps the overall weight of the telescope below 140 tons. To reduce the night sky background it is necessary to limit the signal integration time to a short window only accommodating the Cherenkov signal. A fully isochronous mirror design together with the extremely fast response of the HPDs and the high transmission bandwidth of analog signals over optical fibers will allow us to limit the acquisition window to a few ns. Together with high sampling frequency (2.5 GHz) transient waveform recording techniques, an optimal reduction of the background light can be achieved. By keeping the pixel physical size of the current MAGIC camera while increasing the focal length to 35-40 m, the solid angle sustained by each pixel will be reduced

Table 1. Parameters of the ECO-1000 telescope design

Parameter	Design goal
Mirror dimensions	35 m ⌀, 1000 m^2 area, 780 hex elements of 1.27m^2
Focal ratio f/D	1.1 - 1.2
Mirror profile	parabolic = isochronous
Mirror focusing	continuous active mirror adjustment
Mirror elements	spherical or bi-spherical diamond turned
Dish structure	Dodecahedron space frame
Space frame material	carbon fiber tubes of reduced weight
Telescope weight	$\leq$ 140 t
Turning time 180°	$\leq$ 15 s
Field of view	up to 5°
Camera pixels	$\geq$ 2000
QE (300-600nm)	$\geq$ 40%
Signal rise-time	$\leq$ 0.5 ns
Signal fall-time	$\leq$ 2.0 ns
Signal Transmission	Analog optical transmission (3 GHz bandwidth)
Waveform recording	2.5 GHz sampling

by a factor of 4 maintaining the overall night sky background at similar levels as for MAGIC. The higher resolution of this camera is needed to partly compensate for the early development of low-energy showers in the atmosphere which results in images more concentrated towards the center of the camera [8].

3. Backgrounds

The main background of ground-based gamma-ray astronomy is given by the hadron component of the cosmic ray spectrum. However, at energies below 100 GeV the number of particles above Cherenkov threshold inside the hadronic cascade rapidly decreases with energy. The Cherenkov photon density inside a radius of 120m from the impact point of the air shower is, for proton primaries at high energies, a factor of 2.5 lower than the density produced by showers induced by gamma-rays. At 100 GeV this density drops to 10% and at 10 GeV to ¡1% before practically vanishing. At very low energies the background from primary electrons may become the dominant contribution. This background which accounts for 1% of all incident particles above the atmosphere at 10 GeV, is of special concern as the electromagnetic cascades induced by this type of primary particle are indistinguishable from gamma-ray showers. The Earth's magnetic field deflects low-energy charged particles and thus produces a sharp cutoff at a limiting rigidity. This cutoff is only dependent on the local geomagnetic field

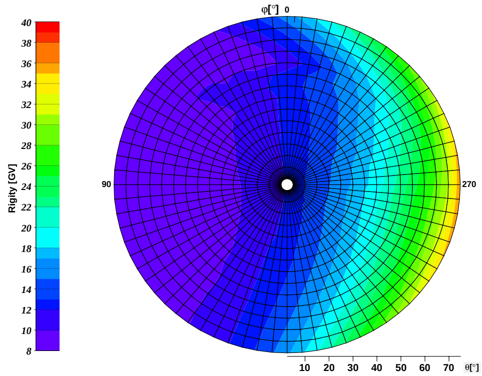

Fig. 1. Cutoff rigidity for electrons in GV plotted versus arrival direction.

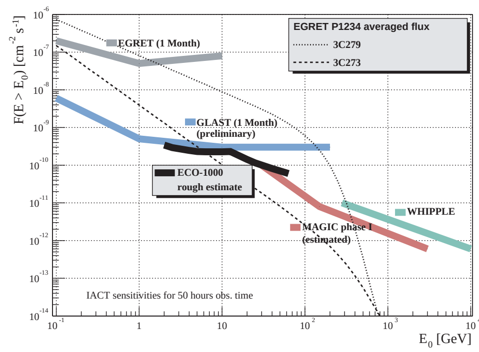

Fig. 2. Estimate of the sensitivity with a ECO-1000 type telescope.

and incident direction of the particle. Using inverse ray tracing it is possible to calculate the cutoff rigidity for all directions at a given location [9]. Using the code developed by Smart and Shea [9] we produced the map shown in Fig. 1. for La Palma, Spain. We can see that for most directions the cutoff rigidity is above 12 GV corresponding to a cutoff energy of 12 GeV for singly charged particles.

4. Expected performance

Assuming a very conservative hadron rejection of 95% while keeping 50% of gammas from image analysis, an effective area derived from Monte Carlo simulations for the MAGIC telescope and shifted down in energy by a factor of 5 (should be a decade if extrapolations would hold) and the proton and electron spectra derived from direct measurements together with a sharp cutoff at 12 GeV due to the geomagnetic field, we derived a rough first estimate of the sensitivity of such a telescope. Figure 2. shows this sensitivity comparing it to the temporally averaged spectra of 3C279 (a typical hard) and 3C273 (a typical soft gamma-ray AGN) as measured by EGRET in the energy range of 100 MeV - 10 GeV.

1. Barrio J.A. et al. 1998, "MAGIC Design Study", MPI Preprint MPI-PhE/98-5
2. Bradbury S. et al. 1997, NIM-A 387, 45
3. Ellis J. et al. 2002, Eur. Phys. J. C24, 311
4. Gebauer J. et al. 2003, NIM A in press
5. Hillas A.M., 1985, in Proc. 19th ICRC (La Jolla), 3, 445
6. Kneiske T.M. et al. 2003, A&A in press
7. Martinez M. et al. 2003, these proceedings
8. Merck M. et al. 2003, in Proceedings of SPIE Vol. 4858, 327
9. Smart D.F., Shea M.A., Flckiger E.O. 2000, Space Sci. Rev. 93, 305
10. Stecker F.W., Fazio G.G. 1970, Nature 226, 135