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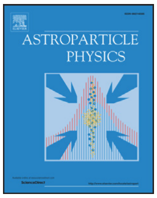

MACHETE: A transit imaging atmospheric Cherenkov telescope to survey half of the very high energy γ-ray sky

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ABSTRACT

Current imaging atmospheric Cherenkov telescopes for very high energy γ-ray astrophysics are pointing instruments with a field of view up to a few tens of sq deg. We propose to build an array of two non-steerable (drift) telescopes. Each of the telescopes would have a camera with a FOV of 5×60 sq deg oriented along the meridian. About half of the sky drifts through this FOV in a year. We have performed a Monte Carlo simulation to estimate the performance of this instrument. We expect it to survey this half of the sky with an integral flux sensitivity of ~0.77% of the steady flux of the Crab Nebula in 5 years, an analysis energy threshold of ~150 GeV and an angular resolution of ~0.1°. For astronomical objects that transit over the telescope for a specific night, we can achieve an integral sensitivity of 12% of the Crab Nebula flux in a night, making it a very powerful tool to trigger further observations of variable sources using steerable IACTs or instruments at other wavelengths.

1. Introduction

Very high energy (VHE; >100 GeV) γ-rays are detected using space-based or ground-based detectors. From space *Fermi*-LAT [1] is performing the deepest survey to date of the γ-ray sky from 20 MeV up to energies in excess of 100 GeV, although with limited sensitivity above 10 GeV due to its relatively small collection area (0.8 m^2).

From the ground imaging atmospheric Cherenkov telescopes (IACTs), such as the MAGIC [2,3], H.E.S.S. [4] or VERITAS [5] arrays, detect γ-rays with energies above 50 GeV and have collection areas of more than 10^5 m^2. They are pointing instruments with a field of view (FOV) on the order of tens of sq deg. The 12 m diameter medium-sized telescopes in the Cherenkov Telescope Array (CTA), currently under design, have a FOV of around 60 sq deg. The telescope mirrors have an area on the order of hundreds of square meters.

On the other hand air-shower instruments such as Milagro [6], Tibet [7] and HAWC [8] detect γ-rays at higher energies (above some hundreds of GeV to typically TeV), have a comparable collection area of ~80,000 m^2, but with a much larger FOV of ~5000 sq deg and high duty cycle. They are non-tracking instruments. Unfortunately they are not as efficient as IACTs in eliminating the cosmic ray background, so they suffer from a lower sensitivity and they have poorer angular or spectral resolutions.

We propose to build an array of two non-steerable IACTs with a wide FOV of 300 sq deg. We call this array Meridian Atmospheric CHErenkov TElescope (MACHETE). MACHETE's FOV is significantly larger than that of all existing IACTs, making it into an instrument suitable for surveys. On the other hand its sensitivity is as good as that of current IACT arrays. In the next sections we describe the instrument, we evaluate its expected performance and we discuss its main physics goals.

2. Telescope design

2.1. Basics of the optical design

Steerable IACTs with wide FOV of tens of sq deg have been proposed [11–14]. Ultra high energy cosmic ray detectors using the fluorescence technique with a very large FOV on the order of steradians are already operational [9] or under design [10], but their light collection area does not exceed a few square meters.

A Schmidt telescope is a well-known solution to achieve a large FOV with a small focal ratio. The optical components are an easy-to-manufacture spherical primary mirror, and an aspherical correcting lens, known as a Schmidt corrector plate, located at the center of curvature of the primary mirror. The corrector plate reduces optical aberrations and at the same time acts as a "stop" which defines the aperture of the telescope. The authors of [14] have in fact proposed a Schmidt IACT with a 7 m diameter primary mirror. Their design is technically challenging though, because the corrector plate is as large as 7 m and it is implemented as a thin tessellated Fresnel lens.

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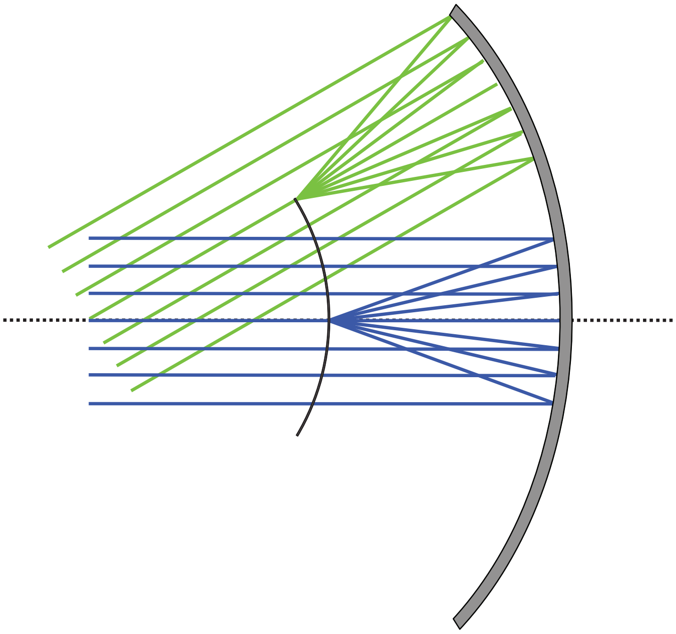

Fig. 1. Layout of the optical elements of MACHETE. The dotted line represents the optical axis. Both mirror (outer grey arc) and focal plane (inner black arc) are concentric. Rays coming parallel to the optical axis and 30° off-axis are represented with correspondingly blue and green lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

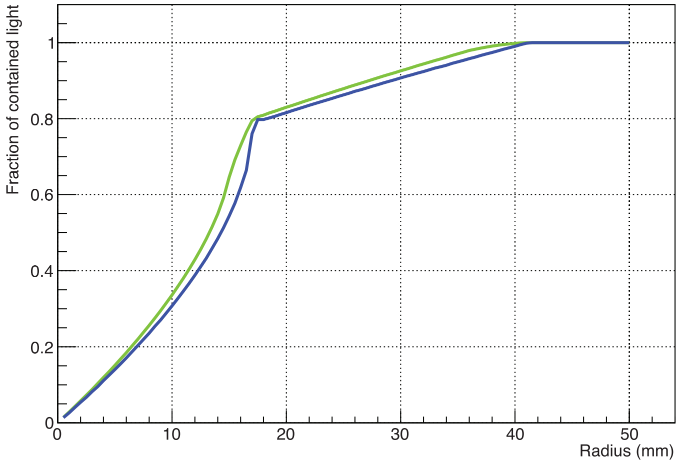

Fig. 2. Fraction of the incident light that is focused inside a given radius around the spot centroid as a function of that radius. The curves correspond to light incident along the optical axis (blue) and light incident 30° off-axis (green). There is hardly any difference between the two curves: r_{80} is 17.5 mm for both of them. The change of slope around 17.5 mm is related to the fact that the camera is not located at the nominal focal distance of the spherical mirror. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Our concept is inspired by a Schmidt telescope, but we have aimed at simplifying it so that it is easy and cheap to implement:

- Like in the original Schmidt telescope, the shape of the primary mirror is spherical. The nominal focal length is half of the radius of curvature.
- Also like a Schmidt telescope, the shape of the focal plane is spherical and concentric with the mirror.
- An IACT is not as stringent as an optical telescope in terms of mirror point spread function (PSF). A PSF on the order of 0.05° is good enough. We shall remove the corrector plate and achieve an acceptable PSF by increasing the focal ratio.
- However if we eliminate the corrector plate we are not only worsening the optical performance of the instrument, but also eliminating the stop. We must find an alternative way to limit the aperture. Compared to optical telescopes IACTs are in fact peculiar because each pixel is typically implemented as a light concentrator, usually a Winston Cone (WC), followed by the actual photodetector. The light concentrator serves three purposes: it limits stray light beyond a certain acceptance angle and it allows to reduce the dead space and the size of the photodetector (and hence its cost). But in a natural way light concentrators can also be used to define the section of the mirror which is viewed by each pixel and effectively the aperture.

For MACHETE we adopt the following optical parameters. The radius of curvature of the mirror is 34 m. We choose an acceptance angle of 20° in the light concentrators. The light concentrators at the camera front follow the curvature of the focal plane. The focal plane is at roughly half of the radius of curvature (17 m), so each point of the camera views a section of the mirror that is circular and has a diameter $D = 12$ m. This means that the aperture becomes effectively 12 m and the focal ratio is $f/D = 1.42$.

Fig. 1 illustrates the concept. We have drawn the optical path of a fan of rays coming parallel to the optical axis and of a fan of rays with a large 30° off-axis angle. The central ray of each of the fans goes through the center of curvature of the mirror and focal plane. As such it arrives perpendicular to both surfaces. The light concentrators limit the extension of the ray fans in Fig. 1 and the effective diameter of the mirror that collects light for every point in the camera.

We have used Zemax (OpticStudio 14.2) to optimize the optical layout of the design. We set the radius of curvature of the mirror to 34 m. We have not simulated the light concentrators. Instead we have defined a 12 m diameter circular stop perpendicular to the incident ray fan and centered at the center of the curvature of both mirror and focal plane. Both scenarios are optically interchangeable if the light concentrators have an ideally sharp cutoff.

The distance from the mirror to the camera front has been optimized to obtain the smallest possible spot size. More specifically we have defined r_{80} as the radius around the centroid of the light spot that encloses 80% of the light and we have minimized r_{80} on-axis. The resulting distance from mirror to camera front is 16.84 m and the radius of curvature of the camera is correspondingly 17.16 m. The plate scale is 300 mm/deg.

Fig. 2 shows the fraction of the incident light that is enclosed within a certain radius around the spot centroid for two angles respect to the optical axis. This fraction has been calculated using Zemax. r_{80} is 17.5 mm for both incident angles, which corresponds to 0.06°. As may be expected there is hardly any difference in r_{80} for any position of the FOV.

This Zemax simulation does not take into account the effect of the spread in the distribution of actual radii of curvature of the facets during the fabrication process or the alignment of the facets during the installation process. We will come back to the error introduced by these two effects in Section 3.

With a camera as large as in Fig. 1 all rays coming parallel to the optical axis are blocked if we assume that the system is symmetric. The rest of the FOV would also suffer from significant shadowing, i.e. the instrument will suffer from strong vignetting. We can however restrict our FOV to a strip of 5° × 60°. Assuming that the focal plane instruments are flat enough and ignoring the focal plane support structure, the shadowing is 16% for most of the FOV and only significantly smaller at the edges of the long arc (at the very edge it is about 8%). In this way we can still achieve a large FOV of 300 sq deg with a very simple optical design.

In a spherical reflector photons from the same direction but hitting the reflector at different distances to the optical axis arrive to the focus at different times. For this specific optical setup, the largest time difference is 3.7 ns and the RMS of the distribution is about 1.5 ns.