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The Galactic Center region imaged by VERITAS

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ABSTRACT

The Galactic Center has long been a region of interest for high-energy and very-high-energy observations. Many potential sources of GeV/TeV γ-ray emission have been suggested, e.g., the accretion of matter onto the black hole, cosmic rays from a nearby supernova remnant, or the annihilation of dark matter particles. The Galactic Center has been detected at MeV/GeV energies by EGRET and recently by Fermi/LAT. At GeV/TeV energies, the Galactic Center was detected by different ground-based Cherenkov telescopes such as CANGAROO, Whipple 10 m, HESS, and MAGIC. We present the results from 15 h of VERITAS observations conducted at large zenith angles, resulting in a >10 standard deviation detection. The combined Fermi/VERITAS results are compared to astrophysical models.

1. Introduction

1.1. The Galactic Center region

The center of our galaxy harbors a $4\times10^6\,M_\odot$ black hole (BH) which is believed to coincide with the strong radio source Sgr A*. At optical wavelengths the view towards the Galactic Center (GC) is hidden by molecular clouds. X-ray transients with 2–10 keV energy output up to 10^{35} ergs/s are observed on a regular basis, as well as transients at MeV/GeV energies.[2] Besides these transients, there are other astrophysical sources located in the close vicinity of the GC which may potentially be capable of accelerating particles to multi-TeV energies, such as the supernova remnant Sgr A East or a plerion [1].

The gravitational potential of our galaxy is believed to bind a halo of dark matter particles – the nature of which is still a matter of very active research. The super-symmetric neutralinos χ are discussed as one potential dark matter particle accumulating in this halo – the density of which sharply spikes at the GC. Neutralinos would annihilate and produce two γ-ray lines, one at the neutralino mass m_χ ($\chi\chi\rightarrow\gamma\gamma$) and one slightly below ($\chi\chi\rightarrow\gamma+Z^0$), as well as a γ-ray continuum at lower energies [2] which could, depending on m_χ, potentially be detected at MeV/GeV/TeV energies. Assuming a certain density profile of the dark matter the expected γ-ray flux along the line-of-sight integral can be calculated as a function of m_χ and the annihilation cross-section [3] and can in turn be compared to measurements or upper limits.

1.2. The Galactic Center seen at GeV/TeV energies

The GC region is crowded with astrophysical sources which can potentially emit γ-rays at MeV/GeV/TeV energies. The limited resolution of instruments in these wave bands makes definite associations challenging. The Egret γ-ray telescope detected a MeV/GeV source 3EG J1746-2851 which is spatially coincident with the GC [4]. Recently, the Fermi/LAT resolved more than one MeV/GeV sources in the GC region [5], where the strongest source is spatially coincident with the GC (Fig. 2). However, uncertainties in the diffuse galactic background models and the limited angular resolution of the Fermi/LAT make it difficult to study the morphologies of these MeV/GeV sources.

At GeV/TeV energies a detection from the direction of the GC was first reported in 2001/02 by the CANGAROO II collaboration which operates a ground-based γ-ray telescope. A steep energy spectrum $dN/dE\propto E^{-4.6}$ was reported with an integral flux at the level of 10% of the Crab Nebula flux [6]. Shortly after, evidence at the level of 3.7 standard deviations (s.d.) was reported from 1995 to 2003 observation conducted at large zenith angles (LZA) with the Whipple 10 m γ-ray telescope [7].

The GC was finally confirmed as a GeV/TeV γ-ray source in a highly significant (>60 s.d.) detection from 2004 to 2006 observations reported by the HESS collaboration [8]. The energy spectrum was well described by a power-law $dN/dE\propto E^{-2.1}$ with a cut-off at ~15 TeV. No evidence for variability was found in the data. Using a high-precision pointing system of the telescopes the

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[1] http://veritas.sao.arizona.edu/.

[2] See for example the recent Astronomer's telegrams #2690, #2770, #2770, #3123, #3162, #3163, #3183.

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position of the supernova remnant Sgr A East could be excluded as the source of the γ-ray emission. After subtracting the point source located at the position of the GC the HESS collaboration was able to identify a diffuse GeV/TeV γ-ray emission. The intensity profile of the diffuse component is found to be aligned along the galactic plane and follows the structure of molecular clouds [9]. The energy spectrum of the diffuse emission (dashed contour lines in Fig. 2) can be described by a power-law $dN/dE \propto E^{-2.3}$ and was explained by an interaction of local cosmic rays with the matter in the molecular clouds – indicating a harder spectrum and a higher flux of cosmic rays in this region as compared to the one observed at Earth.

The MAGIC collaboration detected the GC in 2004/05 observations performed at LZA at the level of 7 s.d. [10], confirming the energy spectrum measured by HESS The differences between the spectrum measured by CANGAROO compared to the other ground-based GeV/TeV instruments can potentially be explained by the fact that different instruments may have seen different (in time) astrophysical sources.

2. Large zenith-angle observations

The standard method of shower reconstruction in arrays of ground-based Cherenkov telescopes (such as VERITAS) is based on the intersection of the major axis of the Hillas images recorded in the individual telescopes [11]. This stereoscopic method is generally very powerful, since it makes use of the full capabilities of the stereoscopic recording of showers. In the following this method is referred to as 'geo' method (geometric method). An alternative technique has been developed long ago for single-telescopes (i.e. Whipple 10 m), using an estimate of the 'displacement' parameter which is measured between the center of gravity (CoG) of the Hillas ellipse and the shower position in the camera system [12]. Throughout this paper the method will be referred to as 'disp' method. The 'disp' method is based on the fact, that the probability density function of γ-ray showers has a well-defined maximum at a characteristic distance (displacement) between the image's CoG and the source position measured in camera coordinates. The characteristic displacement can be parameterized as a function of the length l, the width w, and the amplitude/size s of the corresponding image.

In LZA observations the telescope's locations in the plane perpendicular to the shower axis are 'shrinking' towards one dimension (due to projection effects); this strongly reduces the average stereo angle between the major axes of pairs of images, causing a large uncertainty in the determination of the intersection point. This, in turn, leads to a considerable reduction of the angular resolution in the reconstruction of the shower direction and impact parameter. The 'disp' method, on the other hand, does not rely on the intersection of axes, making it independent of the stereo angle between images. Therefore, no substantial drop in performance is expected with increasing zenith angle. The 'disp' method was implemented into the VERITAS analysis chain. The displacement parameter is parameterized as a function of l, w, s, the zenith angle z, the azimuth angle Az, as well as the pedestal variance of the image. For each image the 'disp' parameter is read from a 6-dimensional look-up table which was trained using MonteCarlo simulations. For each image the corresponding disp parameter results in two most likely points of the shower direction (camera coordinates): CoG $\pm$ 'disp' along the major axis of the parameterized image. The two-fold ambiguity is resolved by combining the points of all images involved in the event. The shower impact parameter is reconstructed in a comparable way.

Fig. 1, left shows the angular resolution of both methods ('geo' and 'disp') as a function of zenith angle z. While the 'disp' method remains almost independent of z, the standard method 'geo' becomes increasingly worse at LZA. A further improvement is achieved if both methods are combined: $d = d_{geo} \cdot (1-w') + d_{disp} \cdot w'$. The weight is calculated as $w' = \exp(-12.5 \cdot (\cos(z) - 0.4)^2)$; for $\cos(z) < 0.4$ the weight is set to $w' = 1$. The method was tested on Crab Nebula data taken at LZA, see Fig. 1, right. The data are in excellent agreement with the simulations and illustrate the clear improvement the 'disp' method provides in the case of LZA observations.

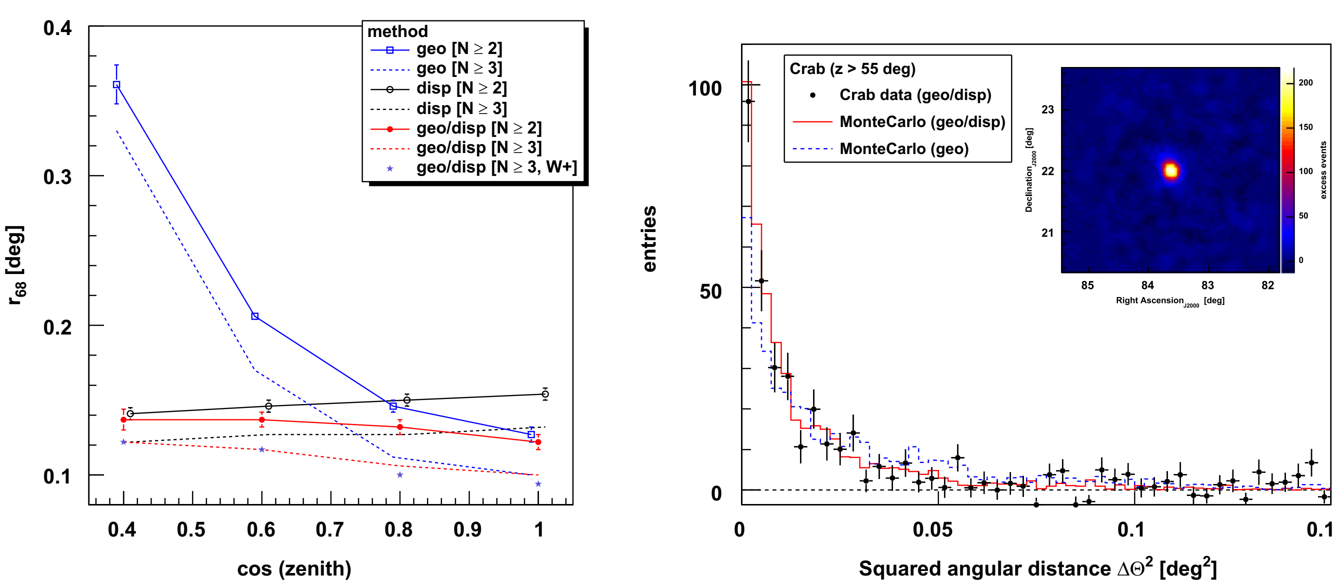

Fig. 1. Left: The VHE angular resolution (r_{68} containment radius) as a function of cos(z). The 'geo' algorithm performs well for zenith angles down to 40° (cos(z) = 0.8) but gets worse below. The 'disp' algorithm does not depend on the stereo angle between image axis and is therefore not sensitive to the zenith angle. At LZA of 65° it outcompetes the 'geo' algorithm by a factor of more than 2. A weighted combination of both algorithms ('geo'/'disp', see text) gives an almost flat angular resolution. Right: The data points show the angular distribution of excess events from 3.5 h of Crab Nebula observations taken at zenith angles $z > 55°$. The showers were reconstructed with the 'geo'/'disp' method. The solid line represents the angular distribution of MonteCarlo events ('geo'/'disp' method) covering the same zenith angle range as the data. The dashed line shows the distribution of Monte Carlo events which were reconstructed with the standard 'geo' algorithm. The inlay shows the corresponding sky map of the Crab Nebula data.