The Galactic Center Region Imaged by VERITAS

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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, H.E.S.S., and MAGIC. We present the results from 15 hrs of VERITAS observations conducted at large zenith angles, resulting in a >10 standard deviation detection and confirmation of the high-energy spectrum observed by H.E.S.S. The combined Fermi/VERITAS results are compared to astrophysical models.

I. INTRODUCTION

A. The Galactic Center region

The center of our galaxy harbors a $4 \times 10^6 M_\odot$ 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 and dust. 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. 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 found in that region.

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 $\chi$ are discussed as one potential dark matter particle accumulating in this halo – the density of which peaks at the GC. Neutralinos could annihilate directly to gamma rays forming narrow lines (through $\chi \chi \rightarrow \gamma \gamma$ or $\chi \chi \rightarrow \gamma + Z^0$) or annihilate to quarks or heavy leptons, hadronizing and producing secondary γ-rays in a continuum. The resulting spectrum would have a cut-off near the neutralino mass $m_\chi$, and a detailed spectral shape determined by the annihilation channel. The resulting signal would typically show up in the GeV/TeV band for natural neutralino parameters. 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 $m_\chi$ and the annihilation cross section and can in turn be compared to measurements or upper limits.

B. 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. Recently, the Fermi/LAT resolved more than one MeV/GeV sources in the GC region, 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 operated 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. Shortly after, evidence at the level of 3.7 standard deviations (s.d.) was reported from 1995-2003 observation conducted at large zenith angles (LZA) with the Whipple 10 m γ-ray telescope.

The GC was finally confirmed as a GeV/TeV γ-ray source in a highly significant (>60 s.d.) detection from 2004-2006 observations reported by the H.E.S.S. collaboration. 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 H.E.S.S. or Whipple data over a time scale of more than 10 years. Using a high-precision pointing
system of the H.E.S.S. telescopes the position of the supernova remnant Sgr A East could be excluded as the source of the $\gamma$-ray emission. After subtracting the point source located at the position of the GC the H.E.S.S. collaboration was able to identify a diffuse GeV/TeV $\gamma$-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. 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 (CRs) with the matter in the molecular clouds – indicating a harder spectrum and a higher flux of CRs in this region as compared to the CRs observed at Earth.

The MAGIC collaboration detected the GC in 2004/05 observations performed at LZA at the level of 7 s.d., confirming the energy spectrum measured by H.E.S.S. The differences between the energy spectrum measured by CANGAROO compared to the spectra measured by the other ground-based GeV/TeV instruments could perhaps be explained if the different instruments observed different astrophysical sources.

II. 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. 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 $geo$ (geometrical) method.

An alternative technique has been developed long ago for data taken with single-telescopes (i.e. Whipple 10m), 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. For $\gamma$-ray showers the displacement parameter has a certain characteristic value as a function of the image parameters. 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. Throughout this paper this method is referred to as $disp$ method.

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* parameter was implemented into the VERITAS analysis chain being parameterized as a function of \( l, w, s, z \), the zenith angle \( z \), and the azimuth angle \( A_z \), as well as the pedestal variance of the image. For each image the corresponding *disp* parameter results in two most likely 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 6-dimensional look-up table which was trained using Monte Carlo simulations. For each image the corresponding *disp* parameter results in two most likely points of the shower direction (camera coordinates): CoG \( \pm \text{disp} \) 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.

Figure 1 left shows the angular resolution of both methods (*geo* and *disp*) as a function of the cosine of the zenith angle \( z \). While the *disp* method remains almost independent of \( \cos(z) \), the resolution of the standard method *geo* becomes increasingly worse at LZA. A further improvement is achieved if both methods are combined: \( d = d_{\text{geo}} \cdot (1 - w') + d_{\text{disp}} \cdot w' \). 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 (Figure 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.

III. THE GALACTIC CENTER REGION IMAGED BY VERITAS

A. VERITAS observations

VERITAS consists of four 12 m diameter imaging atmospheric Cherenkov telescopes and is located at the base camp of the Fred Lawrence Whipple Observatory in southern Arizona at an altitude of 1280 m. VERITAS is sensitive to \( \gamma \)-rays in the energy range of 100 GeV to several tens of TeV. For observations close to zenith a source of 10% (1%) of the strength of the Crab Nebula can be detected at the level of 5 s.d. in 0.5 hrs (26 hrs), respectively.

The GC was observed by VERITAS in 2010 for 14.7 hrs (good quality data, dead-time corrected). Given the declination of the GC, the observations were performed at LZA in the range of \( z = 60.2 - 66.4 \) deg, resulting in an average energy threshold of \( E_{\text{thr}} \approx 2.5 \text{TeV} \). The shower direction and impact parameter were reconstructed with the *geo*/*disp* method as described in Sec. II. Other than that, the standard analysis procedure was applied with standard cuts a-priori optimized for galactic sources. The column density of the atmosphere changes with \( 1/\cos(z) \). In a conservative estimate, the systematic error in the energy/flux reconstruction can be expected to scale accordingly. For the GC observations the contribution of the systematic effect induced by the atmosphere therefore roughly doubles as compared to low-zenith angle observations. Detailed studies are needed for an accurate estimate; for the moment we give a conservative value of a systematic error on the LZA flux normalization of \( \Delta \Phi/\Phi \approx 0.4 \).

B. Results

The VERITAS sky map of the GC region is shown in Fig. 2. An excess on the order of 12 s.d. is detected. A fit of the point spread function to the uncorrelated excess map results in a position of the excess of long = \((-0.06 \pm 0.02) \) deg and lat = \((-0.06 \pm 0.01) \) deg which is well compatible with the GC position (long = \(-0.06 \) deg and lat = \(-0.05 \) deg) and the position mea-
FIG. 3: **Left:** VERITAS energy spectrum measured from the direction of the GC (statistical errors only). Also shown are bow ties representing the spectra measured by Whipple [7], H.E.S.S. [8], and MAGIC [10] (see Sec. I). **Right:** VERITAS energy spectrum compared to hadronic [13, 14] and leptonic [15] emission models discussed for the GC source. The Fermi bow tie is taken from [13].

...sured by H.E.S.S. No evidence for variability was found in the data. The energy spectrum is shown in Fig. 3 and is found to be compatible with the spectra measured by Whipple, H.E.S.S., and MAGIC. Moreover, the uncertainty in the spectrum at energies $E > 2.5 \text{ TeV}$ is found to be comparable to the high-energy H.E.S.S. measurements since the much larger LZA effective area compensates the shorter exposure time. To gain an independent estimate of the systematics of the energy/flux reconstruction at LZA, a 3.5 hrs data set taken on the Crab Nebula at LZA ($z > 55\deg$) was analyzed with the same method as applied for the GC. The reconstructed Crab Nebula spectrum is found to be in reasonable agreement with the H.E.S.S. measurements obtained from lower zenith angles.

**C. Comparison to models**

Astrophysical models have been put in place to explain the GeV/TeV $\gamma$-ray emission from the vicinity of the BH. Hadronic acceleration models [13, 14] explain the emission by the following mechanism: (i) Hadrons are accelerated in the BH vicinity (few tens of Schwarzschild radii). (ii) The accelerated protons diffuse out into the interstellar medium where they (iii) produce neutral pions which decay into GeV/TeV $\gamma$-rays: $\pi^0 \rightarrow \gamma\gamma$. Changes in flux can potentially be caused by changes in the BH vicinity (e.g. accretion). The time scales of flux variations in these models are $\sim 10^4 \text{ yr}$ at MeV/GeV energies (old flares) and $\sim 10 \text{ yr}$ at $E > 10 \text{ TeV}$ (‘new’ flares caused by recently injected high-energy particles) [13]. While not observed over the $\sim 15 \text{ year time frame}$ of Whipple, H.E.S.S., MAGIC, and VERITAS spectral variability can be expected in this model for $E > 10 \text{ TeV}$ with the TeV spectrum softening following an outburst [14].

Atoyan et al. (2004) [15] discuss a BH plerion model in which a termination shock of a leptonic wind accelerates leptons to relativistic energies which in turn produce TeV $\gamma$-rays via inverse Compton scattering. The flux variability time scale in this model is on the order of $T_{\text{var}} \sim 100 \text{ yr}$ and therefore would allow to distinguish hadronic vs. leptonic models in the case that TeV $\gamma$-ray flux variability is detected. The hadronic and the leptonic models discussed in this section are shown together with the VERITAS/Fermi data in Fig. 3 (right). The leptonic model clearly fails in explaining the flux in the MeV/GeV regime. However, this emission may well originate from a spatially different region or mechanism than the TeV $\gamma$-ray emission since the SED indicates a spectral break between the Fermi/LAT and VERITAS energy regimes. The hadronic models can explain the SED by the superposition of different flare stages. Future Fermi/VERITAS flux correlation studies, as well as the measurements of the TeV energy cut-off and limits on the $E > 10 \text{ TeV}$ variability will serve as crucial inputs for the modeling.

**D. Upper limit on diffuse $\gamma$-ray emission and dark-matter annihilation flux**

The VERITAS observations of the GC region were accompanied by OFF-source observations of a field located in the vicinity of the GC region (similar zenith angles and sky brightness) without a known TeV $\gamma$-ray source. These observations can be used to study the...
background acceptance throughout the field of view and will support the estimate of a diffuse $\gamma$-ray component surrounding the position of the GC. An upper limit of the diffuse $\gamma$-ray flux can in turn be compared with line-of-sight integrals along the density profile $\int \rho^2 \, dl$, in order to constrain the annihilation cross section for a particular dark matter model, dark matter particle mass and density profile $\rho(r)$. Due to its likely astrophysical origin the excess at the GC itself, as well as a region along the galactic plane, will be excluded from this analysis (work in progress).

IV. SUMMARY AND CONCLUSION

The implementation of the disp method into the VERITAS data analysis chain substantially improved the shower reconstruction and sensitivity for data taken at LZA and allowed to detect the GC within 3 hrs in $z > 60$ deg observations. The energy spectrum measured from the GC by VERITAS is found to be in agreement with earlier measurements by H.E.S.S., MAGIC, and Whipple. Future observations to measure the cut-off energy in the spectrum and to determine limits on the flux variability at the highest energies will allow to constrain the emission models discussed in the literature. An upper limit on diffuse $\gamma$-ray emission and, in consequence, a limit on the potential photon flux initiated by the annihilation of dark matter particles is work in progress.

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