OBSERVATION OF GAMMA RAYS FROM THE GALACTIC CENTER WITH THE MAGIC TELESCOPE

J. Albert, E. Aliu, H. Anderhub, P. Antoranz, A. Armada, M. Asensio, C. Baixeras, J. A. Barrio, M. Bartelmann, H. Bartko, D. Bastieri, B. Bednarek, K. Berger, C. Bigongiari, A. Biland, E. Bisesi, R. K. Bock, T. Bretz, I. Britvitch, M. Camara, A. Chilingarian, S. Ciprini, J. A. Coarasa, S. Commissarou, J. L. Contreras, J. Cortina, V. Curtef, V. Danilov, F. Dazzi, A. De Angelis, R. De Lotto, F. Domingo-Santamaria, D. Donner, M. Doron, M. Errando, M. Fagioli, D. Ferenc, F. Fernández, R. Firpo, J. Flix, M. F. Fonseca, L. Font, N. Galante, M. Garca-Recio, M. Gaug, M. Gillier, F. Goebel, D. Hakobyan, M. Hayashida, T. Hengstebeck, D. Höhne, J. Höse, P. Jacon, O. Kakehin, M. Kanbach, A. Lallement, T. Lenisa, P. Liebing, E. Lindfors, F. Longo, J. López, M. López, E. Lorenz, E. Lucarelli, P. Majumdar, G. Manev, K. Mannheim, M. Mariotti, M. Martínez-González, K. Mase, M. Mazin, M. Merck, M. Meucci, M. Meyer, K. J. Miramanda, R. Mirzoyan, S. Mizobuchi, A. Moralejo, K. Nilsson, E. Oña-Wilhelmi, R. Orduña, N. Otte, I. Oya, D. Paneque, R. Paolletti, M. Pasanen, D. Pascoli, F. Pauss, N. Pavel, R. Peig, L. Peruzzo, A. Piccioni, E. Prandini, J. Rico, W. Rhode, B. Riegel, M. Rissi, A. Robert, S. Rügamer, A. Saggion, A. Sánchez, P. Sartori, V. Scalzotto, R. Schmitt, T. Schweizer, M. Shyudyak, K. Shinozaki, S. N. Shorer, N. Sidro, A. Sillanpää, D. Sobczynska, A. Stamerra, A. Stepanian, L. S. Stark, L. Takalo, P. Temnikov, D. Tescaro, M. Teshima, N. Tonello, A. Torres, D. F. Torres, N. Turini, H. Vankov, A. Vardanyan, V. Vitale, R. M. Wagner, T. Wibig, W. Wittek, J. Zapatero

ABSTRACT

Recently, the Galactic Center has been reported to be a source of very high energy (VHE) γ-rays by the VERITAS, CANGAROO and HESS experiments. The energy spectra as measured by these experiments show substantial differences. In this Letter we present MAGIC observations of the Galactic Center, resulting in the discovery of a differential γ-ray flux consistent with a steady, high-slope power law, described as \(dN_{\gamma}/(d\text{d}t dE) = (2.9 \pm 0.6) \times 10^{-12} (E/\text{TeV})^{-2.2 \pm 0.2} \text{ cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}\). The γ-ray source is located in the direction of Sgr A* (LaRosa et al. 2000). The dynamical center of the Milky Way is believed to be a massive black hole (Morris & Serabyn 1996). Within a radius of 10 pc around the GC there is a mass of about 3 \(10^7 M_\odot\) (Schödel et al. 2002).

EGRET has detected a strong source in the direction of the GC, 3 EG J1745-2852 (Mayer-Hasselwander et al. 1998), which has a broken power law energy spectrum extending up to at least 10 GeV, with a spectral index of 1.3 below the break at a few GeV. Assuming a distance of the GC of 8.5 kpc, the γ-ray luminosity of this source is very large, 2.2 \(10^{37}\) erg/s, which is equivalent to about 10 times the γ-ray flux from the Crab nebula. However, an independent analysis of the EGRET data (Hooper & Dingus 2002) indicates a point source whose position is different from the GC at a confidence level beyond 99.9 %. This was recently sustained by Pohl (2005).

In very high energy γ-rays the GC has been observed by VERITAS, CANGAROO and HESS (Kosack et al. 2004, Tsuchiya et al. 2004, Aharonian et al. 2004). The energy spectra as measured by these experiments show substantial differences. This might be due to different sky integration regions of the signal or a source variability at a time-scale of about one year.

1. INTRODUCTION

The Galactic Center (GC) region contains many remarkable objects which may be responsible for high-energy processes generating γ-rays (Aharonian & Neronov 2003, Atwood & Dermer 2004). The GC is rich in massive stellar clusters with up to 100 OB stars (Morris & Serabyn 1996), immersed in a dense gas. There are young supernova remnants, e.g. Sgr A East, and nonthermal radio arcs located on the Canary Island La Palma (28.8°N, 17.8°W, 1338 m) is currently the largest single dish imaging Air Cherenkov Telescope (IACT) in operation. Located on the Canary Island La Palma (28.8°N, 17.8°W, 3782 m) is currently the largest single dish imaging Air Cherenkov Telescope (IACT) in operation.
The telescope has a 17-m diameter tessellated parabolic mirror, supported by a light weight carbon fiber frame. It is equipped with a high quantum efficiency 576-pixel 3.5° field-of-view photomultiplier camera. The analog signals are transported via optical fibers to the trigger electronics and are read out by a 300 MSamples/s FADC system.

At La Palma, the GC ((RA, Dec) = (17°45′36″, −28°56′)) culminates at about 58° zenith angle (ZA). The star field around the GC is non-uniform. In the region west of the source (RA > RA_{GC} + 4.7′′) the star field is brighter. Within a distance of 1° from the GC there are no stars brighter than 8th magnitude.

The MAGIC observations were carried out in the ON/OFF mode as well as in the false-source tracking (wobble) mode (Fomin et al. 1994). The sky directions (W1, W2) to be tracked in the wobble mode are chosen such that in the camera the star field relative to the source position (GC) is similar to the star field relative to the mirror source position (anti-source position): W1/W2 = (RA_{GC}, Dec_{GC} ± 0.4°). During one wobble mode data taking, 50% of the data is taken at W1 and 50% at W2, switching between the two positions every 20 minutes. Dedicated OFF data have been taken, with a sky field similar to that of the ON region. The OFF region is centered at the Galactic Plane, GC_{OFF} = (RA, Dec) = (17°51′12″, −26°52′00″). In the same night OFF data was taken directly before or after the ON observations under the same weather conditions and hardware setup.

After initial observations in September 2004 the GC was observed for a total of about 24 hours in the period May-July 2005. Table 1 summarizes the data taken.

### Table 1: Data Set

| Period | date         | ZA [°] | time [h] | events [10⁶] | obs. mode |
|--------|--------------|--------|----------|--------------|-----------|
| I      | Sep. 2004    | 62-68  | 2        | 0.8          | ON        |
| II     | May 2005     | 58-62  | 7        | 2.8          | wobble    |
| III    | Jun./Jul. 2005 | 58-62 | 17/12    | 6.4/5.0      | ON/OFF    |

NOTE.— Data set per observation period of the GC. The column “time” states the effective observation time, the column “events” states the events after image cleaning.

The source-position independent image parameters SIZE, WIDTH, LENGTH, CONC (Hillas 1985) and the third moment of the ph. el. distribution along the major image axis, as well as the source-position dependent parameter DIST (Hillas 1985), were selected to parameterize the shower images. After the training, the Random Forest method allows to calculate for every event a parameter, called hadronness, which is a measure of the probability that the event is not γ-like. The γ-sample is defined by selecting showers with a hadronness below a specified value. An independent sample of MC γ-showers was used to determine the efficiency of the cuts.

The analysis at high zenith angles was developed and verified using Crab data with a ZA around 60°. The determined Crab energy spectrum was found to be consistent with other existing measurements (see Fig. 3, dot-dashed line).

For each event the arrival direction of the primary in sky coordinates is estimated by using the DISP-method (Fomin et al. 1994; Lessard et al. 2001; Domingo-Santamaria et al. 2005).

For the sky map calculation only source independent image events drawn from the measured OFF-data. The MC γ-showers were generated between 58° and 68° ZA with energies between 10 GeV and 30 TeV. For the analysis of the September 2004 data set the Random Forest cuts were determined using a sub-set of Galactic OFF data as background.

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parameters are used in the Random Forest training. Figure 1 shows the sky map of γ-ray candidates (background subtracted, see e.g. [Rowell 2003]) from the GC region (observation periods II/III). It is folded with a two-dimensional Gaussian with a standard deviation of 0.1° (roughly corresponding to the MAGIC PSF) and height one. A lower SIZE cut of 300 ph. el. has been applied, corresponding to an energy threshold of about 1 TeV. The sky map is overlayed with contours (0.3 Jy beam⁻¹) of 90 cm VLA (BCD configuration) radio data from [LaRosa et al. 2000]. The brightest non-central source is the Arc. The excess is centered at (RA, Dec) = (17h45m20s, -29°2') (J2000 coordinates). The systematic pointing uncertainty is estimated to be 2' (for description of the MAGIC telescope drive system see [Bretz et al. 2003]) and might in the future be further reduced with the MAGIC starfield monitor [Riegel et al. 2005]. The excess is compatible with a point source emission. The VHE γ-ray source G 0.9+0.1 [Aharonian et al. 2005] is located inside the MAGIC field-of-view. It shows a small excess consistent with the low flux reported by [Aharonian et al. 2005]. The MAGIC excess is not yet statistically significant for the given exposure time.

Figure 2 shows the distribution of the squared angular distance, θ², between the reconstructed shower direction and the nominal GC position corresponding to Fig. 1 (observation periods II/III). The observed excess in the direction of the GC has a significance of 7.3 standard deviations (θ² ≤ 0.02°). The source position and the flux level are consistent with the measurement of HESS [Aharonian et al. 2004] within errors.

For the determination of the energy spectrum, the Random Forest was trained including the source dependent image parameter DIST with respect to the nominal excess position. For the spectrum determination only the largest data set (period III) was used. The cut on the hadronness parameter (50% γ-efficiency corresponding to an effective area of about 250000 m²) resulted in about 500 excess events with a minimum SIZE of 200 ph. el. Figure 3 shows the reconstructed VHE γ-ray energy spectrum of the GC after the unfolding with the instrumental energy resolution, see [Mizobuchi et al. 2005]. The differential γ-flux can be well described by a simple power law:

$$\frac{dN}{dA dt dE} = (2.9 \pm 0.6) \times 10^{-12} (E/\text{TeV})^{-2.2\pm0.2} \text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1} \text{sr}^{-1}.$$

The given errors (1σ) are purely statistical. The systematic error is estimated to be 35% in the flux level determination and 0.2 in the spectral index.

Figure 4 shows the reconstructed integral VHE γ-ray flux above 1 TeV as a function of time. All OFF data are used for each time bin resulting in some correlation between the time bins. Different observation modi may result in different systematic errors. The flux level is steady within errors in the time-scales explored within these observations, as well as in the two year time-span between the MAGIC and HESS observations.

![Graph showing reconstructed VHE γ-ray flux](image)

**Fig. 4.** Light curve: Reconstructed integral VHE gamma-ray flux above 1 TeV as a function of time. Within errors (1σ) the data are consistent with a steady emission.

4. DISCUSSION

Recent observations of TeV γ-rays from the GC confirm that this is a very important region for high energy processes in the Galaxy. In fact, this is not surprising since many different objects, able to accelerate particles above TeV energies, are expected there. The most likely source seems to be the massive black hole identified with Sgr A* due to the directional consistency. A blazar-like relativistic jet originating from the spinning GC black hole might be expected to produce TeV γ-rays [Falcke et al. 1993], but flux predictions of this model are on the low side due to an unfavorable orientation of the jet axis. Moreover, a short-term variability would be expected, [Atovian & Dermer 2004] propose that electrons can be accelerated to sufficiently high energies at the termination shock of the sub-relativistic wind from the central part of the advection dominated accretion flow onto the GC black hole, in analogy to the pulsar wind nebulae. The authors explain the broad band emission from Sgr A* (from radio to TeV γ-rays) and suggest that the GeV source observed by EGRET has another origin. This is consistent with the recent determination of the position of the EGRET source 3EG J1746-2851 by [Hooper & Dingus 2002] and [Pohl 2005]. Other scenarios for the γ-ray production in the vicinity of Sgr A*, both leptonic and hadronic, have also been found to be consistent with the TeV observations (for reasonable sets of parameters) but not with the GeV observations [Aharonian & Neronov 2005].
It is generally expected that γ-rays produced in such compact source models should show relatively fast variability. The same level of TeV flux reported by HESS in 2004 and by MAGIC in 2005, and also during their own observation periods extending over a few months, rather suggest a stable source on a year time scale. However, the γ-ray flux above 2.8 TeV (3.7σ significance) reported by Whipple during the extended period from 1995 through 2003 is a factor ∼ 2 larger (Kosack et al. 2004). The origin of γ-ray emission in other types of sources is also possible as demonstrated by the detection of the second TeV γ-ray source in the direction of the GC consistent with the location of the composite supernova remnant SNR G 0.9+0.1 (Aharonian et al. 2005). Pohl (1997) proposed that the TeV emission can be related to the GC radio arc. Crocker et al. (2005), see also Fatuzzo & Melia (2003), argue for the GeV and TeV emission coming from different sites of the shell of the very powerful supernova remnant Sgr A East. More extended γ-ray emission might also originate in the interaction of relativistic particles with the soft radiation and matter of the central stellar cluster around the GC. These particles can be accelerated by e.g. a very energetic pulsar, a γ-ray burst source, shocks in the winds of the massive stars, or a shell type supernova remnant (Bednarek 2002; Grasso & Maccione 2005). If the TeV γ-rays are produced by leptons scattering off the infrared photons from the dust heated by the UV stellar radiation (as discussed by Fatuzzo & Melia 2003), see also Aharonian et al. (2004)) on a time scale of the order 10^7 years. Aharonian et al. (2004) measured a TeV γ-ray flux at a significance of 7σ, Aharonian et al. (2004) on a time scale of the order 10^7 years. Aharonian et al. (2004) measured a TeV γ-ray flux at a significance of 7σ, while the measured flux is compatible with the measurement of HESS (Aharonian et al. 2004) within errors. The γ-ray energy spectrum below 10 TeV shows no significant time variability; our measurements rather affirm a steady emission of γ-rays from the GC region. The excess is point like, its location is spatially consistent with SgrA* as well SgrA East. The nature of the source of the VHE γ-rays has not yet been identified. Future simultaneous observations with the present Cherenkov telescopes, the GLAST telescope and in the lower energies will provide much better information on the source localization and variability of emission. This will shed new light on the nature of the high energy processes in the GC.

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