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Observations of the first unidentified TeV γ-ray source (TeV J2032+4130) with the MAGIC telescope

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Abstract: The TeV source J2032+4130 is the first ever detected unidentified VHE gamma-ray source. There have been contradictory claims regarding its extension, flux level and variability in γ-rays, although the longest and most sensitive observation up to now favor a steady, extended source. MAGIC has devoted more than 80 hours on J2032+4130 during 2005 and 2006. We present the most recent results obtained with the MAGIC telescope on this source.

Introduction

The TeV source J2032+4130 [1], [2] is one the most enigmatic detections in high energy astrophysics. As discussed below, there have been various claims on its spatial extension, flux level, and time variability in γ-rays as observed with different facilities, although the longest and most sensitive observation up to now favors a steady, extended source. Its counterpart at lower energies is yet unknown. It was the first unidentified γ-ray source found at very high γ-ray energies, and also the first-discovered, likely galactic TeV source which appeared to be extended. These properties were to be shared by other detections made more recently with the HESS telescopes.

It was first reported by the HEGRA collaboration [3]. About 113 hours of data recorded during 3 years of regular observations (from 1999 to 2001) were analyzed. The detection was confirmed [2] by follow-up observations (about 158 hours) in 2002. The source was determined to be steady in flux over the four years of data taking, extended, with radius $6.2 \pm 1.2_{\rm stat} \pm 0.9_{\rm sys}$ arcmin, and exhibiting a hard spectrum with a photon index $-1.9 \pm 0.1_{\rm stat} \pm 0.3_{\rm sys}$. Its integral flux above $E > 1$ TeV was found to be $\sim$ 5% of the Crab, assuming a Gaussian profile for the intrinsic source morphology. The center of the source position was determined at $\alpha_{2000} = 20^h31^m57^s$, $\delta_{2000} = 41°29'56.8''$.

Previously, the Crimean group reported a significant excess ($\sim 6.0\sigma$ pre-trial) and the flux of this source above 1 TeV was reported to be 3×10^{-11} cm^{-2} s^{-1} [4]. However, this flux claim was never followed up in subsequent journal publications of the same collaboration, or confirmed by other experiments.

The Whipple collaboration also reported an excess at the position of the HEGRA unidentified source (3.3σ) in their archival data of 1989 and 1990 [5]. The average flux detected in 1989-1990 by Whipple ($\sim$ 12% of the Crab for E>600 GeV) is above the average steady flux reported by HEGRA over the four year observation period. Recently, the Whipple collaboration reported new observations of this field with its 10-m telescope for 65.5 hours during 2003 and 2005 [6]. They find a pretrial excess with a significance of 6.1σ. Given the $\sigma = 7.6'$ width of the PSF of their telescope, their data is consistent with both, a point-like or an extended source with less than $6'$ angular size. Regarding the observed source position, HEGRA and recent Whipple data are barely in agreement: their centers being $\sim 9'$ apart. The flux levels seems also barely consistent: Recent Whipple claims do not provide a spectrum for this source, but just give a 8% Crab-level flux (although with no energy threshold provided) under the assumption of a steep (Crab-like) spectrum and 1.7 kpc distance (the one to Cyg OB2 association).

Finally, the MILAGRO scan [7], shows an excess in the Cygnus region, although it comes from a more extended region and could be a superposition of individual objects plus diffuse emissions.

Several attempts have been done to identify the source in different wavelengths, i.e. [8], [9], [10], [11], [12]. No clear counterpart has been found (more details in [13]).

MAGIC Observations

The MAGIC single dish Imaging Air Cherenkov Telescope (see e.g., Baixeras et al. 2004, Cortina et al. 2005 for a detailed description) is located on the Canary Island La Palma (28.8°N, 17.8°W, 2200 m a.s.l.). Its angular (energy) resolution is approximately 0.09° (20%), and the trigger (analysis) threshold is 55 (60) GeV [14]. The data analysis was carried out using the standard MAGIC analysis and reconstruction software [15], the first step of which involves the calibration of the raw data [16]. After calibration, image cleaning tail cuts of 10 photoelectrons (PE) for image core pixels and 5 PE (boundary pixels) have been applied. These tail cuts are accordingly scaled for the larger size of the outer pixels of the MAGIC camera. The images are parameterized by image parameters [17]. In this analysis, the Random Forest method (see [18], [19] for a detailed description) was applied for the γ/hadron separation and for energy estimation. The source position-independent image parameters SIZE, WIDTH, LENGTH, CONC and the third moment of the PE distribution along the major image axis were selected to parameterize the shower images. After the training, the Random Forest method allows to calculate for every event a parameter, the 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, which

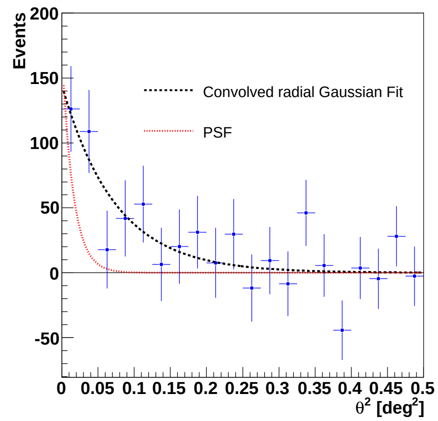

Figure 1: Distribution of θ^2 parameter for events coming from the direction of TeV J2032+4130, the background distribution subtracted (blue points). A PSF convolved radial Gaussian fit is indicated by the dashed black line with $\sigma_{src} = 6.1 \pm 1.8$ arcmin.

is optimized using a sample of Crab data which has been processed with the same analysis stream. An independent sample of Monte Carlo γ-showers was used to determine the cut efficiency.

Since part of our observations were carried out in the presence of partial Moon shine, we have corrected the efficiency loss due to the increase of ambient light. The correction factor and other details for moon-shine observations with MAGIC is discussed by [20].

A total of 86.8 h were devoted to TeV J2032+4130, spammed during 2005 and 2006. The observation zenith angle ranges from 12 to 43^o. During the first period in Summer 2005 the observations were carried out in ON/OFF mode, that is, the source was observed on-axis and observations from an empty field of view were used to estimate the background. Lately, in Summer 2006, the data were taken in the so-called wobble mode, using five positions around the HEGRA position instead the usual two symmetrical position in order to be able to monitor a wider field of view. Applying a lower SIZE cut on the images of 800 PE, the total number of γ-like excess after cuts is $N_{excess} = 268$, with a significance of 6.0σ. The SIZE cut at 800 PE was chosen in account of the hardness of the source spectral index, measured by HEGRA. No indication of time variability is observed: the source integral flux remains constant within the errors at the level of 3.7% of the Crab Nebula during 2005 and 2006.

The θ^2 distribution is calculated for the source position, being θ the angular distance between the source position in the sky and the reconstructed arrival position of the shower. The reconstruction of individual γ-ray arrival directions makes use of the so-called DISP method [21]. The expected number of background events are calculated using five regions symmetrically distributed for each wobble position with respect to the center of the camera and referred to as anti-sources. Fig. 2 shows the distribution of θ^2 parameter for the excess registered in the direction of the source, for a SIZE cut of 800 PE. The excess is fitted to a Gaussian function folded with the telescope point spread function PSF obtained from Monte Carlo simulation and validated with Crab observations. The source appears extended within the MAGIC PSF. Its intrinsic extension assuming a Gaussian profile is σ_{src} =6.1±1.8$_{sta}$ arcmin.

Fig. 2 shows the Gaussian-smoothed map (σ=4') of the field of view (0.7$^o\times$0.7^o) around the TeV J2032+4130 position for a lower cut in the image number of PE of 800 along with the position of Cyg X-3, the EGRET source 3EGJ2033+41 and the results of the best fits to the Whipple and HEGRA data. To determine the best position of the MAGIC detection the excess map was fitted to a 2d Gaussian function. The result is shown in the skymap with a black cross as well as a circle indicating its extension. The best position is RA = (20.537±0.003$_{stat+sys}$) hr and DEC = (41.52±0.02$_{stat+sys}$) ^{o} (for more details on the systematic uncertainties in the source position determination, see Bretz et al, 2003).

The TeV J2032+4130 energy spectrum was obtained using the Tikhonov unfolding technique [22] and is shown in Fig.3. It can be fitted ($\chi^2/n.d.f = 0.3$) by a power law function: dN/dE dA dt = (4.67±0.08)$\times 10^{-13}$(E/1TeV)$^{-1.82\pm0.2}$. The errors quoted only refer to the statistical errors. The systematic error is estimated to be 35% in the flux level determination while it amounts 0.2 for the spectral index, [14]. The differential energy spectrum is shown in Fig.3. The spectrum of HEGRA TeV J2032+4130 as measured by HEGRA and the spectrum of the Crab Nebula as measured by MAGIC [14] are shown in blue solid line and red dotted line respectively. For illustrative purposes we also show in Figure 3 the spectra which are predicted by one-zone hadronic and a simple leptonic model of the high energy emission. Under the hadronic scenario, the π^0-predictions is obtained from a proton parent population described with a power law (index -2) with exponential cutoff at 100 TeV. The inverse Compton spectrum is obtained from an electron population described with equal index and a 40 TeV exponential cutoff scattering off CMB photons. Both models are compatible with the high energy emission. Confirming the reality of the diffuse emission detected at lower energies

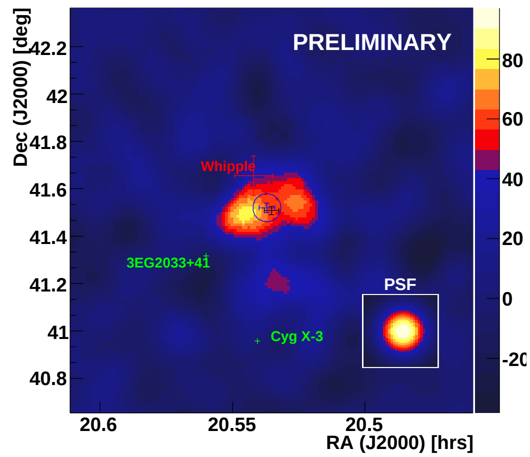

Figure 2: Gaussian-smoothed (σ=4') map of γ-ray excess events (background-subtracted) for a lower SIZE cut of 800 PE for which the angular resolution optimizes. The last position reported by Whipple is marked with a red cross. The HEGRA and MAGIC positions are shown in the center of the field of view with blue and black crosses respectively. The surrounding circle corresponds to their measured 1σ extension. The error bars, in both cases, correspond to the linear sum of the statistical and systematic errors. The green crosses correspond to the positions of Cyg X-3 and the EGRET source 3EGJ2033+41.

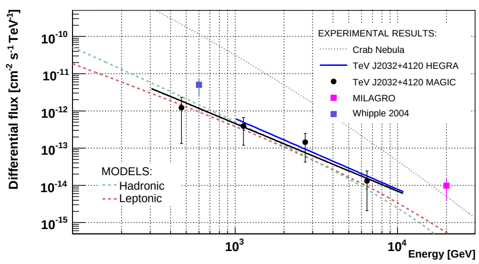

Figure 3: Differential energy spectrum from the TeV J2032+4130 measured with the MAGIC telescope. The flux observed by Whipple in 2005 and in the MILAGRO scan are marked with colored squares.

is crucial to distinguish between these and more complex models (e.g., [23]).

Concluding remarks

In summary, MAGIC observations confirm the location found by HEGRA as well as the extended nature of TeV J2032+4130. MAGIC obtains a steady flux with no significant variability within the two year span of the observation carried over (with the flux being at a similar level when compared even with the HEGRA data of the period 2002-2005). MAGIC also presents the source spectrum obtained with the lowest energy threshold to date, which, within errors, is compatible with a single power law.

Acknowledgments

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