MAGIC OBSERVATIONS OF THE UNIDENTIFIED $\gamma$-RAY SOURCE TeV J2032+4130

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ABSTRACT

We observed the first known very high energy (VHE) $\gamma$-ray-emitting unidentified source, TeV J2032+4130, for 94 hr with the MAGIC telescope. The source was detected with a significance of 5.6 $\sigma$. The flux, position, and angular extension are compatible with the previous ones measured by the HEGRA telescope system 5 years ago. The integral flux amounts to (4.5 $\pm$ 0.3 _stat_ $\pm$ 0.35 _sys_) $\times$ 10$^{-11}$ photons cm$^{-2}$ s$^{-1}$ above 1 TeV. The source energy spectrum, obtained with the lowest energy threshold to date, is compatible with a single power law with a hard photon index of $\Gamma = -2.0 \pm 0.3_{\text{stat}} \pm 0.2_{\text{sys}}$.

Subject heading: gamma rays: observations

1. INTRODUCTION

The TeV source J2032+4130 (Aharonian et al. 2002) was the first unidentified very high energy (VHE) $\gamma$-ray source, and also the first discovered extended TeV source, likely to be Galactic.

Intensive observational campaigns at different wavelengths

have been carried out on TeV J2032+4130. Butt et al. (2003) presented an analysis of the CO, H I, and infrared emissions, together with first observations by Chandra (5 ks) and a reanalysis of VLA data. These observations showed that the TeV source region is positionally coincident with an outlying group of stars (from the Cygnus OB2 core), although they failed to identify a counterpart. Mukherjee et al. (2003) analyzed the same Chandra data and provided optical follow-up observations of several of the brightest X-ray sources, confirming that most were either O stars or foreground late-type stars. A deeper Chandra observation (50 ks; Butt et al. 2006) found hundreds of starlike sources and yet no diffuse X-ray counterpart emission.

A deep (~50 ks) XMM-Newton exposure has also been obtained (Horns et al. 2007). After the subtraction of the contribution of known sources from the data, an extended X-ray emission region with a FWHM size of ~12' was reported. The centroid of the emission is colocated with the position of TeV J2032+4130 and was proposed as the counterpart of the TeV source. The question of whether the result reported by Horns et al. can be interpreted as a truly diffuse background, or whether it could be a result of unresolved X-ray sources, remains disputable.

Paredes et al. (2007) and Martí et al. (2007) have provided deep radio observations covering the TeV J2032+4130 vicinity using the Giant Metrewave Radio Telescope and discovered a population of radio sources, some in coincidence with X-ray detections by Butt et al. (2006) and with optical/IR counterparts. At least three of these sources are nonthermal, and one
TABLE 1

| Year | Time (hr) | Zenith Angle (deg) | Mode |
|------|-----------|--------------------|------|
| 2005 | 18.1      | 13–30              | ON/OFF |
| 2006 | 60.1      | 11–44              | Wobble |
| 2007 | 15.5      | 11–30              | Wobble |

has a hard X-ray energy spectrum. They found extended non-
thermal diffuse emission in the radio band apparently con-
necting with one or two radio sources. It is yet to be determined
whether one or more of these sources is similar to some of the
known γ-ray binaries (e.g., Aharonian et al. 2006; Albert et al.
2006a).

Several theoretical explanations for the TeV emission from J2032+4130 have been given. Among them, those related to
extragalactic counterparts, e.g., a radio galaxy (Butt et al. 2006)
or a proton blazar (Mukherjee et al. 2003), face the difficulty
of explaining the extended appearance of the source. Gamma-
ray production in hypothetical jet termination lobes of Cyg X-
3 was explored (Aharonian et al. 2002), but the putative north-
ern lobe of Cyg X-3 (now considered a mere thermal H II
region; Martí et al. 2006) is far from the location of the TeV
source. A yet unknown pulsar wind nebula (PWN) was pro-
posed by Bednarek (2003), although no clear PWN signal was
observed. A distant microquasar was proposed by Paredes et
al. (2007), perhaps related to one of the X-ray/radio sources
they discovered. If such an association is accepted, the exten-
sion of the source could be explained by the diffusion of ac-
celerated particles into a hypothetical nearby molecular en-
vironment could be explained by the diffusion of ac-
celerated particles into a hypothetical nearby molecular en-
vironment (see Bosch-Ramon et al. 2005). Torres et al. (2004)
and Domingo-Santamaría & Torres (2006) studied the rela-
tion between the TeV emission and the known massive stars in
the area, through the interaction of relativistic protons
with wind ions. The distribution of stars in the neighborhood
favors this interpretation (Butt et al. 2006). An explanation
involving the excitation of giant dipole resonances of relativ-
istic heavy nuclei in radiation-dominated environments has also
been suggested (Anchordoqui et al. 2007).

2. PREVIOUS VERY HIGH ENERGY γ-RAY OBSERVATIONS

We start by making a brief summary of what has been
called by other experiments observing at the highest energies.

The HEGRA IACT, using 4 years of data (from 1999 to
2002), found a source to the north of Cygnus X-3, steady in
flux over the years, extended, with radius 6.2 ± 1.2_{stat} ±
0.9_{sys}, and exhibiting a hard energy spectrum with a photon
index of \( \Gamma = -1.9 \pm 0.1_{stat} \pm 0.3_{sys} \) (Aharonian et al. 2005).
Its integral flux above 1 TeV amounts to ∼5% of the Crab
Nebula, assuming a Gaussian profile for the intrinsic source
morphology. The center of the source position was determined
quite accurately at

\[ \alpha = 20^\mathrm{h}31^\mathrm{m}57.0^\mathrm{s} \pm 6.2_{\mathrm{stat}} \pm 13.7_{\mathrm{sys}} \]  
\[ \delta = 41^\circ 29'056.8'' \pm 1.1_{\mathrm{stat}} \pm 1.0_{\mathrm{sys}} \]  

(J2000.0).

The Whipple collaboration reported an excess at the position
of the HEGRA unidentified source (3.3 \( \sigma \)) in their archival data
of 1989 and 1990 (Lang et al. 2004), with a flux level of ∼12% of
the Crab Nebula for \( E > 600 \) GeV. The detected flux is in
conflict with the HEGRA flux level and steady nature of the
source, assuming they all have the same origin. This large
difference between the detected flux levels, if physical, might
suggest episodic emission (with low duty cycle) or variability
to timescale measured in years. Nevertheless, the existence

of γ-ray variability is difficult to reconcile with the extended
appearance of the source. The large difference might also be
due in part to unspecified systematic errors on the flux deter-
mination. Recently, the Whipple collaboration reported new
observations of this field done with their 10 m telescope for
65.5 hr during 2003 and 2005 (Konopelko et al. 2007). Their
data are consistent with either a pointlike or an extended source
with less than 6′ angular size. Regarding the position, the HE-
GRA and the latest Whipple data are barely in agreement: their
centers of gravity are ∼9′ apart, and only agree when adding
up the spatial uncertainties in both data sets in opposite direc-
tions. Konopelko et al. do not provide a energy spectrum for
this source, but give a 8% Crab-level flux (although with no
energy threshold specified) under the assumption of a steep
(Crab-like) energy spectrum.

The Cygnus region shows an excess in the MILAGRO data
(Adbo et al. 2007). The flux at 20 TeV in a \( 3^\circ \times 3^\circ \) region
centered at the HEGRA position is \( (9.8 \pm 2.9_{\mathrm{stat}} \pm 2.7_{\mathrm{sys}}) \times 10^{-15} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \) assuming a differential energy spectrum
\( E^{-2.6} \). This flux is 3 times the HEGRA flux extrapolated at
20 TeV. The Tibet air shower detector recently reported evidence
for an excess also in their VHE γ-ray candidate set from this
region (Amenomori et al. 2006).

In this rich observational and theoretical context we report
here on MAGIC telescope observations of TeV J2032+4130.

3. MAGIC OBSERVATIONS AND RESULTS

The MAGIC single-dish Imaging Air Cerenkov Telescope
(see, e.g., Cortina et al. 2005 for a detailed description) is
located on the Canary Island of La Palma. Its angular (energy)
resolution is approximately 0.09″ (20%), and the trigger (anal-
ysis) threshold is 55 (60) GeV at zenith in dark conditions (see
Albert et al. 2008). One of the unique characteristics of MAGIC
is its capability of observing under moderate moonlight illu-
mination (Albert et al. 2007a), albeit with a slightly elevated
threshold.

The field of view of TeV J2032+4130 was observed with
MAGIC for more than 100 hr distributed in 2005, 2006, and
2007 (see Table 1). During the first period in summer 2005,
the observation was carried out in ON/OFF mode, that is, the
source was observed on-axis while observations from an empty,
neighboring field of view were used to estimate the background.
In summer 2006 and 2007, the data were taken in Wobble mode,
using five positions around the HEGRA position instead of the
usual two symmetrical position in order to monitor a wider
field of view. Quality cuts based on the trigger and after-clean-
rating were applied in order to remove bad weather runs
and data spoiled by car or satellite light flashes. After these
quality cuts the total observation time is 93.7 hr. The energy
range for which we report these results is significantly above
the aforementioned trigger and analysis threshold energies due
to the fact that the observations were scheduled during moon-
light and at relatively high zenith angles (up to 44°).

The data analysis was carried out using the standard MAGIC
analysis and reconstruction software (Bretz & Wagner 2003).
It follows the general stream explained in Albert et al. (2006b,
2006c, 2006d). After calibration and two levels of image clean-
ing (for image core and boundary pixels, see Fegan 1997), the
camera images are parameterized by the so-called image
parameters (Hillas 1985). The random forest method
was applied for the γ/hadron separation (Albert et al. 2007b).
Using this method a parameter, dubbed hadronness (H), can
be calculated for every event and is a measure of the probability
that the event is not $\gamma$-like. The $\gamma$-like sample is selected for images with $H$ below a specified value, which is optimized using a sample of Crab Nebula data processed with the same analysis stream. An independent sample of Monte Carlo $\gamma$-showers was used to determine the cut efficiency. Since part of our observations was recorded during partial moonshine, we have corrected the efficiency loss due to the increase of ambient light following the procedure outlined in Albert et al. (2007a).

The $\theta^2$-distribution was calculated, $\theta$ being the angular distance between the source direction and the reconstructed arrival direction of the showers. The reconstruction of individual $\gamma$-ray arrival directions makes use of the DISP method (Domingo-Santamaria et al. 2005). The expected number of background events is calculated using five regions symmetrically placed for each wobble position with respect to the center of the camera and referred to as antisources. Figure 1 shows the distribution of TeV J2032+4130 (SIZE $>800$ photoelectrons), the background distribution subtracted ($\theta^2$ parameter). A convolved radial Gaussian fit $F = A \exp\left[-0.5\theta^2/(\sigma_{\text{rad}}^2 + \sigma_{\text{src}}^2)\right]$ is indicated by the solid black line with $\sigma_{\text{rad}} = 5.0'$ $\pm 1.7'$. The $\sigma_{\text{src}}$ was measured from MC simulation and validated with Crab Nebula observations to be $\sigma_{\text{src}} = 5.2' \pm 0.1'$ (dashed black line).

**Figure 1**—Distribution of the $\theta^2$-parameter for events coming from the direction of TeV J2032+4130 (SIZE $>800$ photoelectrons), the background distribution subtracted (black points). A convolved radial Gaussian fit $F = A \exp\left[-0.5\theta^2/(\sigma_{\text{rad}}^2 + \sigma_{\text{src}}^2)\right]$ is indicated by the solid black line with $\sigma_{\text{rad}} = 5.0'$ $\pm 1.7'$. The $\sigma_{\text{src}}$ was measured from MC simulation and validated with Crab Nebula observations to be $\sigma_{\text{src}} = 5.2' \pm 0.1'$ (dashed black line).

The $\theta^2$-distribution was used to determine the $\gamma$-ray background subtracted for energies above 500 GeV. The MAGIC position is shown with a black cross. The surrounding black circle corresponds to the measured $1\sigma$ width. The last position reported by Whipple is marked with a white cross while the HEGRA position is shown with a blue cross in the center of the field of view. The error bars, in all cases, correspond to the linear sum of the statistical and systematic errors. The green crosses correspond to the positions of Cyg X-3, WR 146, and the EGRET source 3EG J2033+4118. The ellipse around the EGRET source marks the 95% confidence contour.

**Figure 2**—Gaussian-smoothed ($\sigma = 4'$) map of $\gamma$-ray excess events (background subtracted) for energies above 500 GeV. The MAGIC position is shown with a black cross. The surrounding black circle corresponds to the measured $1\sigma$ width. The last position reported by Whipple is marked with a white cross while the HEGRA position is shown with a blue cross in the center of the field of view. The error bars, in all cases, correspond to the linear sum of the statistical and systematic errors. The green crosses correspond to the positions of Cyg X-3, WR 146, and the EGRET source 3EG J2033+4118. The ellipse around the EGRET source marks the 95% confidence contour. The excess map was fitted to a 2D bell-shaped function. The result is shown in the sky map with a black cross and a circle indicating its size. The best-fit coordinates are R.A. $= 20^h32^m20^s \pm 11^{\prime\prime}_{\text{stat}} \pm 11^{\prime\prime}_{\text{sys}}$, decl. $= 41^\circ30'36.0'' \pm 1.2^{\prime\prime}_{\text{stat}} \pm 1.8^{\prime\prime}_{\text{sys}}$ (J2000.0; for more details on the systematic uncertainties in the source position determination, see Bretz & Wagner 2003).

**Table 2**

| Year   | $N_{\text{ex}}$ | $N_{\text{fit}}$ | $N_{\text{src}}$ | $f_{\text{norm}}$ | $N_{\text{fit}}$ |
|--------|-----------------|------------------|------------------|-------------------|-----------------|
| 2005   | 641             | 554              | 65               | 0.47              | 2.2             |
| 2006   | 688             | 559              | 129              | 0.20              | 4.8             |
| 2007   | 175             | 136              | 39               | 0.20              | 2.9             |
| Overall| 1304            | 1271             | 233              | 0.27              | 5.6             |

**Notes.** $N_{\text{ex}}, N_{\text{fit}},$ and $N_{\text{src}}$ refer to the number of events recorded in the direction of the source, the normalized background, and the $\gamma$-ray excess, respectively. The normalization ratio $f_{\text{norm}}$ and significance $N_{\text{fit}}$ are also shown.

**Table 3**

| Target Name | Flux (Crab Nebula) |
|-------------|--------------------|
| Cyg X-3     | 0.011              |
| WR 146      | 0.010              |
| 3EG J2033+4118 | 0.009            |
The position found is compatible within errors with the one determined by HEGRA, and barely compatible with the claims by Whipple mentioned above (in Konopelko et al. 2007).

The TeV J2032+4130 energy spectrum was obtained using the Tikhonov unfolding technique (Tikhonov & Arsenin 1979). It can be fitted ($\chi^2$/dof = 0.3) by a power-law function. The differential flux ($E^{-2.0 \pm 0.3}$) is

$$\frac{dN}{dE \, dA \, dt} = (4.5 \pm 0.3) \times 10^{-13} \left( \frac{E}{1 \, \text{TeV}} \right)^{-2.0 \pm 0.3}.$$ (1)

The errors quoted are only statistical. The systematic error is estimated to be 35% in the flux level and 0.2 in the photon index (see Albert et al. 2008). The differential energy spectrum shown in Figure 3. The HEGRA TeV J2032+4130 and MAGIC Crab Nebula measured spectra (in Albert et al. 2008) are shown with the blue solid line and black dotted line, respectively. The MAGIC energy spectrum is compatible both in flux level and photon index with the one measured by HEGRA.

Crab Nebula data from the same periods and zenith angle distributions were studied with the same analysis chain to check for any systematic deviation due to the long observation period. No indication of time variability was observed: the source integral flux is constant within errors, at 3 of the Crab Nebula flux. The relative systematic uncertainty in the ratio of both fluxes was estimated to be less than 10%. This uncertainty comes mainly from the slightly different atmospheric transmission conditions and differences in the detector parameters during data taking of the source and the Crab Nebula.

For illustrative purposes, the dotted lines in Figure 3 represent one-zone hadronic and leptonic models of the high-energy emission, both consistent with observations at lower energies in the region. Under the hadronic scenario, the $\pi^0$ are obtained from a proton parent population described by a power law ($\Gamma = -2$) with exponential cutoff at 100 TeV. The cutoff value was adopted to be consistent with the upper limit at the highest energies coming from the HEGRA spectrum. The inverse Compton spectrum is obtained from an electron scattering off the CMB photons. As in Aharonian et al. (2005), we do not consider here the conditions under which particles are accelerated or how they lose energy. Our leptonic fits (see also the quoted paper for an SED representation) can only cope with the data if we are actually looking at a Compton peak around the energy range of detection, which is not fully discarded within errors. Both models are compatible with the high-energy emission. Confirming the reality of the diffuse emission detected at lower energies is crucial to distinguish between these and more complex models.

4. CONCLUDING REMARKS

MAGIC observations confirm the location of TeV J2032+4130 found by HEGRA. The MAGIC observation shows an extended source with a significance of 5.6 $\sigma$. We find a steady flux with no significant variability within the 3 year span of the observations (with the flux being at a similar level to the HEGRA data of the period 2002–2005). We also present the source energy spectrum obtained with the lowest energy threshold to date, which, within errors, is compatible with a single power law.

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