

DISCOVERY OF VHE GAMMA RADIATION FROM IC 443 WITH THE MAGIC TELESCOPE

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ABSTRACT

We report the detection of a new source of very high energy (VHE, $E_\gamma \geq 100$ GeV) γ -ray emission located close to the Galactic Plane, MAGIC J0616+225, which is spatially coincident with SNR IC 443. The observations were carried out with the MAGIC telescope in the periods December 2005 - January 2006 and December 2006 - January 2007. Here we present results from this source, leading to a VHE γ -ray signal with a statistical significance of 5.7 sigma in the 2006/7 data and a measured differential γ -ray flux consistent with a power law, described as $dN_\gamma/(dAdt dE) = (1.0 \pm 0.2) \times 10^{-11} (E/0.4\text{TeV})^{-3.1 \pm 0.3} \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$. We briefly discuss the observational technique used and the procedure implemented for the data analysis. The results are placed in the context of the multiwavelength emission and the molecular environment found in the region of IC 443.

Subject headings: gamma rays: observations — supernovae remnants — ISM:individual (MAGIC J 0616+225, IC 443)

1. INTRODUCTION

IC 443 is an asymmetric shell-type SNR with a diameter of 45 arc minutes at a distance of about 1.5 kpc (Fesen 1984; Claussen et al. 1997). It is included in Green's catalog (Green 2004), and it has a spectral index of 0.36, and

a flux density of 160 Jy at 1 GHz. It was mapped in radio with the VLA at 90 cm (Claussen et al. 1997) and at 20, 6 and 3.5 cm (Olbert et al. 2001; Condon et al. 1998). Moreover, Claussen et al. (1997) reported the presence of maser emission at 1720 MHz from four sources, the strongest of which is located at $(l, b) \sim (-171.0, 2.9)$. IC 443 is a prominent X-ray source, with data available from Rosat (Asaoka & Aschenbach 1994), ASCA (Keohane et al. 1997), XMM (Bocchino & Bykov 2000, 2001, 2003; Bykov et al. 2005; Troja et al. 2006), and Chandra (Olbert et al. 2001; Gaensler et al. 2006). The EGRET has detected a γ -ray source above 100 MeV in the IC 443 SNR, 3EG J0617+2238 (Eposito et al. 1996; Hartman et al. 1999). Upper limits to the very high energy (VHE) γ -ray emission from IC 443 were reported by the Whipple collaboration: $dN_\gamma/(dAdt) < 6 \times 10^{-12} \text{cm}^{-2}\text{s}^{-1}$ (0.11 Crab) above 500 GeV (Holder 2005) and by the CAT collaboration $dN_\gamma/(dAdt) < 9 \times 10^{-12} \text{cm}^{-2}\text{s}^{-1}$ above 250 GeV (Khelifi 2003).

Here we present observations of the SNR IC 443 with the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope resulting in the detection of a new source of VHE γ -rays, named MAGIC J0616+225. We briefly discuss the observational technique used and the procedure implemented for the data analysis, derive a VHE γ -ray spectrum, and analyze it in comparison with other observations, including the molecular environment found in the region of IC 443.

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2. OBSERVATIONS

MAGIC (see e.g., Baixeras et al. (2004); Cortina et al. (2005) for a detailed description) is the largest single dish Imaging Air Cherenkov Telescope (IACT) in operation²⁵. It is located on the Canary Island La Palma (28.8°N, 17.8°W, 2200 m a.s.l.).

The SNR IC 443 was observed for a total of 10 hours in the period December 2005 - January 2006 (period I), with the telescope pointing to the SNR center. The VHE γ -ray sky map showed evidence for a VHE γ -ray signal with a statistical significance of 3σ (before trials were taken into account). To test the hypothesis that this excess is due to a VHE γ -ray source, MAGIC J0616+225, the excess center was observed for a total of 37 hours in the period December 2006 - January 2007 (period II). Therefore, in the analysis of the period II data no trial factors needed to be taken into account to compute the statistical significance of the source detection. Changes in the readout chain in spring 2006 due to the installation of a novel 2 GSamples/s FADC system (Bartko et al. 2005; Goebel et al. 2007) in parallel to the existing 300 MSamples/s FADC system made it advisable (on grounds of simplicity of the analysis) to select only the second part of the dataset, period II, for the studies presented here. However, within statistics the data from period I provide compatible results.

At La Palma, IC 443 culminates at about 6° zenith angle (ZA). The observations were carried out in the false-source tracking (wobble) mode (Fomin et al. 1994). The sky directions (W1, W2) to be tracked were on two opposite sides of the source direction, at a distance of 0.4° from the source. They were chosen such that in the camera the sky brightness distribution relative to W1 was similar to the one relative to W2. For each tracking position three circular background control regions were defined, located symmetrically to the source region with respect to the camera center. During wobble mode data taking, 50% of the data was taken at W1 and 50% at W2, switching (wobbling) between the 2 directions every 20 minutes. In total, about 8 million triggers were recorded in period I and about 30 million triggers were recorded in period II. There are two bright stars in the field of view: η Gem (mag(V) = 3.28 and B - V = 1.60) at a distance to MAGIC J0616+225 of 0.4° and μ Gem (mag(V) = 2.88 and B - V = 1.64) at a distance of 1.9° to MAGIC J0616+225. Both stars are rather red such that the increase in the pixel anode currents is still sustainable at nominal pixel high voltage (Albert et al. 2007b; Paneque et al. 2004). The discriminator thresholds of the channels included in the trigger are dynamically regulated to keep the individual pixel rates at a constant level (Cortina et al. 2005).

3. DATA ANALYSIS

Data runs with anomalous trigger rates due to bad observation conditions (three nights of data taking) were rejected from further analysis. In addition, data with ZA > 30° (2 h) were excluded. The remaining data set corresponded to an effective observation time (including a dead-time correction) of 29 h.

The data analysis was carried out using the standard MAGIC analysis and reconstruction software (Bretz & Wagner 2003), the first step of which involves the FADC signal reconstruction using a digital filter and the calibration of the raw data (Albert et al. 2006d; Gaug et al.

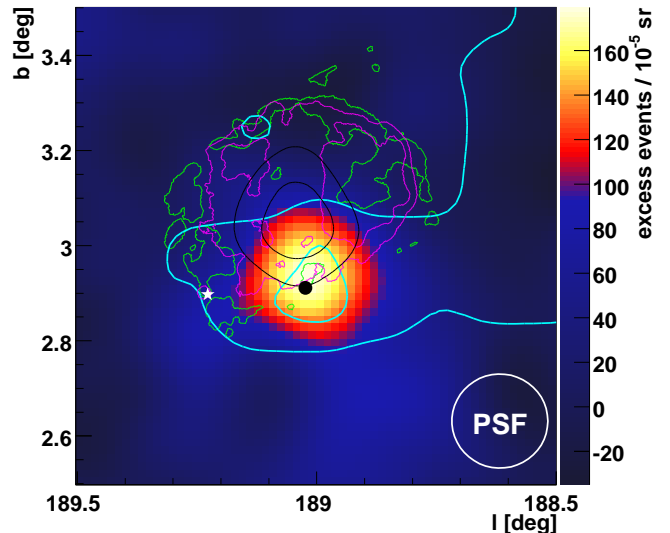


FIG. 1.— Sky map of γ -ray candidate events (background subtracted) in the direction of MAGIC J0616+225 for an energy threshold of about 150 GeV in galactic coordinates. Overlaid are ^{12}CO emission contours (cyan) from Dame et al. (2001), contours of 20 cm VLA radio data from Condon et al. (1998) (green), X-ray contours from Rosat (Asaoka & Aschenbach 1994) (purple) and γ -ray contours from EGRET (Hartman et al. 1999) (black). The ^{12}CO contours are at 7 and 14 K km/s, integrated from -20 to 20 km/s in velocity, the range that best defines the molecular cloud associated with IC 443. The contours of the radio emission are at 5 mJy/beam, chosen for best showing both the SNR IC 443. The X-ray contours are at 700 and 1200 counts / $6 \cdot 10^{-7}$ sr. The EGRET contours represent a 68% and 95% statistical probability that a single source lies within the given contour. The white star denotes the position of the pulsar CXOU J061705.3+222127 (Olbert et al. 2001). The black dot shows the position of the 1720 MHz OH maser (Claussen et al. 1997). The white circle shows the MAGIC PSF of $\sigma = 0.1^\circ$.

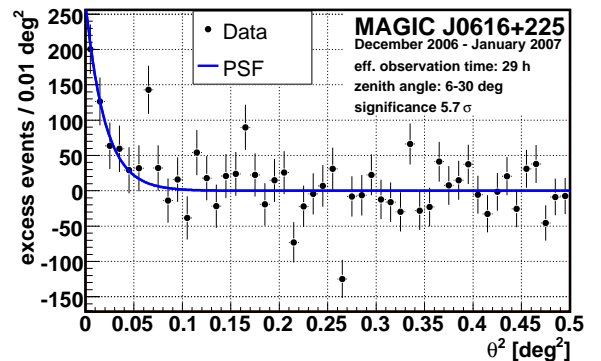


FIG. 2.— Distribution of excess γ -ray candidate events (figure 1) as a function of the squared angular distance from the excess center of MAGIC J0616+225 (points), compared to the expected distribution for a point-like source (blue line) corresponding to the MAGIC PSF.

2005). Thereafter, shower images were cleaned by applying a cut of 10 photoelectrons (ph. el.) for image core pixels and 5 ph. el. for boundary pixels, respectively (see e.g. (Fegan 1997)). These tail cuts were scaled for the larger size of the outer pixels of the MAGIC camera. The camera images were characterized by image parameters (Hillas 1985). In this analysis, the Random Forest method (see Bock et al. (2004); Breiman (2001) for a detailed description) was applied for the γ /hadron separation (for a review see e.g. Fegan (1997)) as well as for the energy estimation, see e.g. Albert et al. (2006a,b,c, 2007b). Above the analysis energy threshold,

²⁵ see also <http://wwwmagic.mppmu.mpg.de/magic/factsheet/>

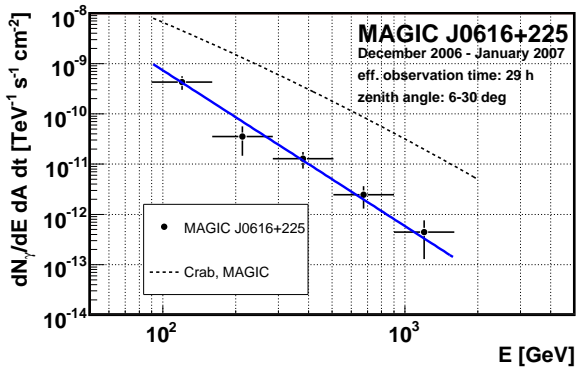


FIG. 3.— VHE γ -ray spectrum of MAGIC J0616+225 (statistical errors only). The full line shows the result of a simple power law fit to the spectral points taking into account correlations between the spectral points that are introduced by the unfolding procedure. The dashed line shows the spectrum of the Crab Nebula as measured by MAGIC (Albert et al. 2007b).

the cut efficiency reaches about 50% corresponding to an effective collection area for γ -ray showers of about 50000 m^2 .

For each event the arrival direction of the primary γ -ray candidate in sky coordinates was estimated using the DISP-method (Fomin et al. 1994; Lessard et al. 2001; Domingo-Santamaria et al. 2005). A conservative cut of $\text{SIZE} \geq 200$ ph. el. was applied to select a subset of events with superior angular resolution. For these events the effect of the bright stars in the field of view is negligible. The corresponding analysis energy threshold (the energy corresponding to the maximum of the differential γ -ray rate after all analysis cuts) was about 150 GeV.

Figure 1 shows the sky map of γ -ray candidates (background subtracted) from the direction of MAGIC J0616+225 in galactic coordinates. It was folded with a two-dimensional Gaussian with a standard deviation of 0.072° . The MAGIC γ -ray PSF (standard deviation of a two-dimensional Gaussian fit to the non-folded brightness profile of a point source) is $(0.10 \pm 0.01)^\circ$ for $\text{SIZE} \geq 200$ ph.el. (Domingo-Santamaria et al. 2005). The folding of the sky map serves to increase the signal-to-noise ratio by smoothing out statistical fluctuations. However, it correlates the values of neighbouring bins and somewhat degrades the spatial resolution. The sky map is overlaid with contours of ^{12}CO emission (cyan) from Dame et al. (2001), contours of 20 cm VLA radio data from Condon et al. (1998) (green), X-ray contours from Rosat (purple) (Asaoka & Aschenbach 1994) and γ -ray contours from EGRET (Hartman et al. 1999) (black). Also XMM-Newton and Chandra X-ray observations of IC 443 exist; they will be discussed below. The white star denotes the position of the pulsar CXOU J061705.3+222127 (Olbert et al. 2001). The black dot shows the position of the 1720 MHz OH maser (Claussen et al. 1997). The VHE γ -ray sky map shows a clear excess centered at (RA, DEC) = $(06^{\text{h}}16^{\text{m}}43^{\text{s}}, +22^\circ 31' 48'')$, MAGIC J0616+225. The statistical position error is $1.5'$, the systematic error due to background determination and pointing uncertainty is estimated to be $1'$ (Albert et al. 2007b). Within errors MAGIC J0616+225 is point-like. The center of gravity of the excess in the period II data presented here agrees with the center of gravity of the excess in the period I data not shown here.

Figure 2 shows for the excess γ -ray-like events in figure 1 the distribution of the squared angular distance, θ^2 , with respect to the excess center together with the expected distri-

bution for a point-like source. Choosing a conservative θ^2 cut of $\theta^2 \leq 0.05 \text{ deg}^2$, as appropriate for unidentified sources, the observed excess in the period II data set in the direction of MAGIC J0616+225 has a significance of 5.7σ . The period I data showed an excess of about 3σ significance at a position less than $3' = 0.05^\circ$ away from period II data set. Computing the significance of the period II data set with respect to the period I position yields only a negligible difference for the chosen large signal region $\theta^2 \leq 0.05 \text{ deg}^2$. Choosing smaller θ^2 cuts, one obtains a higher significance for the period II excess center.

For the spectral analysis the excess data from a sky region of maximum angular distance of $\theta^2 = 0.05 \text{ deg}^2$ around the excess center were integrated. Figure 3 shows the reconstructed VHE γ -ray spectrum ($dN_\gamma / (dE_\gamma dA dt)$ vs. true E_γ) of MAGIC J0616+225 after correcting (unfolding) for the instrumental energy resolution (Anykeev et al. 1991; Bertero 1989). The horizontal bars indicate the bin size in energy. A simple power law was fitted to the spectral points taking into account correlations between the spectral points that are introduced by the unfolding procedure. The result is given by ($\chi^2 / \text{n.d.f} = 1.1$):

$$\frac{dN_\gamma}{dA dt dE} = (1.0 \pm 0.2) \times 10^{-11} \left(\frac{E}{0.4 \text{ TeV}} \right)^{-3.1 \pm 0.3} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}.$$

The quoted errors are statistical. The systematic error is estimated to be 35% in the flux level determination and 0.2 in the spectral index, see also Albert et al. (2006b, 2007b). The integral flux of MAGIC J0616+225 above 100 GeV is about 6.5% and above 300 GeV about 2.8% of the Crab Nebula flux. The integral flux of MAGIC J0616+225 in the observation period II is compatible within errors with that of period I. Within the two observation periods (two months each) no flux variations exceeding the measurement errors were observed. All data analysis steps were cross-checked by a second, independent analysis, yielding compatible results.

4. DISCUSSION AND CONCLUDING REMARKS

If, due to the spatial association shown in Figure 1, we accept that MAGIC J0616+225 is associated with SNR IC 443, located at a distance of ~ 1.5 kpc, then it has a luminosity between 100 GeV and 1 TeV of about $2.7 \times 10^{33} \text{ erg s}^{-1}$. This is roughly one order of magnitude below the luminosity of the sources HESS J1813-178 and J1834-087 (Aharonian et al. 2006), both also detected by MAGIC (Albert et al. 2006a,c). In addition, the γ -ray spectrum of MAGIC J0616+225 is steeper than those of J1813-178 and J1834-087.

Figure 1 indeed shows a very interesting multi-frequency phenomenology. First, it can be noted that the MAGIC VHE γ -ray source is slightly displaced with respect to the central position of the EGRET source 3EG J0617+2238, although still consistent with it, within errors. An independent analysis of GeV photons measured by EGRET resulted in the source GeV J0617+2237 (Lamb & Macomb 1997), that is at the same location of 3EG J0617+2238. Gaisser et al. (1998); Baring et al. (1999) and Kaul (2001) extrapolate the energy spectrum of 3EG J0617+2238 into the VHE γ -ray range. The predicted fluxes are higher with a harder energy spectrum than MAGIC J0616+225. This supports the view that a direct extrapolation of the EGRET source to the MAGIC energy range is not valid.

The EGRET source is located in the center of the SNR, whereas the VHE γ -ray source is displaced to the south,

in direct correlation with a molecular cloud. The molecular cloud environment surrounding IC 443 and its possible connection with the EGRET γ -ray source was studied by Torres et al. (2003), who also provided a review of previous measurements regarding this SNR environment. There is a large amount of molecular mass ($\lesssim 10^4 M_{\odot}$) consistent with the distance to the SNR IC 443, corresponding to a velocity range of -20 to 20 km/s, as shown in Figure 1. The highest CO intensity detected is directly superimposed on the central position of the MAGIC source. Moreover, Claussen et al. (1997) reported the presence of maser emission from $(l, b) \sim (-171.0, 2.9)$, spatially correlated with the MAGIC source (see also Hewitt et al. (2006)). The maser emission is an indication for a shock in a high matter density environment. It is assumed to be due to collisionally excited H_2 molecules heated by the shock.

An electronic bremsstrahlung hypothesis for the origin of the EGRET source (e.g., Bykov et al. (2000)) is difficult to reconcile with the fact that the radio synchrotron, X-rays, and optical emission is concentrated towards the rim of the remnant, whereas the EGRET source is located in the center. On the other hand, the optical emission seems to fade in regions where CO emission increases and where the MAGIC source is located (see Lasker et al. (1990)). This perhaps indicates that the molecular material, which absorbs the optical radiation, is at the remnant's nearest side. The report by Cornett (1977) also argues that the molecular mass is located between us and the SNR. Similarly, the recent analysis of XMM observations by Troja et al. (2006) reached the same conclusions. The observed VHE γ -radiation may be due to π^0 -decays from interactions between cosmic rays accelerated in IC 443 and the dense molecular cloud. A possible distance of this cloud from IC 443 could explain the steepness of the VHE γ -ray spectrum measured. As has been emphasized by Aharonian & Atoyan (1996), the observed γ -rays can have a significantly different spectrum from that expected from the particle population at the source (the SNR shock).

The positions of 3EG J0617+2238, GeV J0617+2237, and

MAGIC J0616+225 are all different from that of the pulsar wind nebula (PWN) CXOU J061705.3+222127 (Olbert et al. 2001; Bocchino & Bykov 2001). The PWN is now co-located with a high density molecular material region (Seta et al. 1998), which in addition is excited, as measured by a high $CO(J=2-1)/CO(J=1-0)$ ratio. If the VHE γ -ray emission were related to the PWN, one may expect some spatial overlap between the PWN and the γ -ray sources.

A complete coverage of the X-ray emission from the region was made with XMM (Bocchino & Bykov 2003), resulting in the detection of 12 X-ray sources with fluxes larger than 5×10^{-14} erg cm $^{-2}$ s $^{-1}$. None of these sources is spatially coincident with the MAGIC detection reported here. Rather, they are mostly located in the relatively small, 15 arcmin \times 15 arcmin region, for which the analysis of the 2MASS data reveals strong 2.2 μ m emission indicating interaction with a molecular cloud. The MAGIC source, uncorrelated with X-ray sources, is, however, also co-spatial with a region of high 2.2 μ m emission, but farther away from the shock.

In summary, the observation of IC 443 using the MAGIC Telescope has led to the discovery of a new source of VHE γ -rays, MAGIC J0616+225, near the Galactic Plane. A reasonably large data set was collected and the spectrum of this source was measured up to energies of 1.6 TeV. The differential energy spectrum can be fitted with a power law of slope $\Gamma = -3.1 \pm 0.3$. The coincidence of the VHE γ -ray source with SNR IC 443 poses this SNR as a natural counterpart, and although the mechanism responsible for the high energy radiation remains yet to be clarified, a massive molecular cloud and OH maser emissions are located at the same sky position as that of MAGIC J0616+225, and suggest that a nucleonic origin of the VHE γ -rays is possible.

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