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Search for gamma-ray emission from the Supernova Remnants W66, W44 and IC443 with the MAGIC Telescope

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Abstract: SNRs in general, and in particular, those SNRs which might be physically related with EGRET sources were chosen as a target for observations with the MAGIC telescope. Here we report about the searches for VHE gamma-ray emission from the SNR IC443. We briefly describe the observational strategy, the procedure implemented for the data analysis, and discuss the results.

Introduction

IC 443 is an asymmetric shell-type SNR with a diameter of 45 arc minutes at a distance of about 1.5 kpc [1, 2]. It is included in Green's catalog [3], 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 [2] and at 20, 6 and 3.5 cm [4, 5]. Moreover, [2] 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 [6], ASCA [7], XMM [8, 9, 10, 11, 12], and Chandra [4, 13]. The EGRET has detected a γ-ray source above 100 MeV in the IC 443 SNR, 3EG J0617+2238 [14]. Upper limits to the very high energy (VHE) γ-ray emission from IC 443 were reported by the Whipple collaboration: $\mathrm{d}N_\gamma/(\mathrm{d}A\mathrm{d}t) < 0.6 \times 10^{-7}\mathrm{m}^{-2}\mathrm{s}^{-1}$ (0.11 Crab) above 500 GeV [15] and by the CAT collaboration $\mathrm{d}N_\gamma/(\mathrm{d}A\mathrm{d}t) < 0.9 \times 10^{-7}\mathrm{m}^{-2}\mathrm{s}^{-1}$ above 250 GeV [16].

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. See also [17].

Observations

MAGIC (see e.g., [18, 19] for a detailed description) is the largest single dish Imaging Air Cherenkov Telescope (IACT) in operation[1]. The SNR IC 443 was observed for a total of 47 hours in the period December 2005 - January 2007, for further information see [17]. Details regarding the calibration and data analysis can be found in [20, 21, 22, 23, 24, 25].

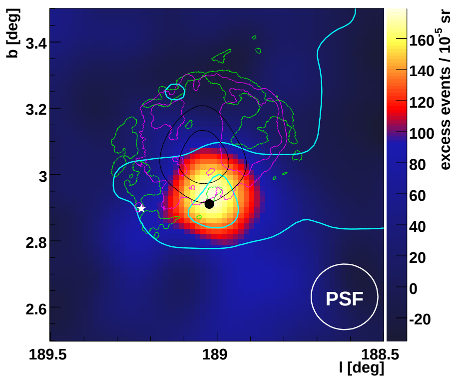

Figure 1: Sky map of γ-ray candidate events (background subtracted) in the direction of MAGIC J0616+225 for an energy threshold of about 150 GeV in galactic coordinates. Overlayed are ^{12}CO emission contours (cyan) from [26], contours of 20 cm VLA radio data from [5] (green), X-ray contours from Rosat [6] (purple) and γ-ray contours from EGRET [14] (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 [4]. The black dot shows the position of the 1720 MHz OH maser [2].

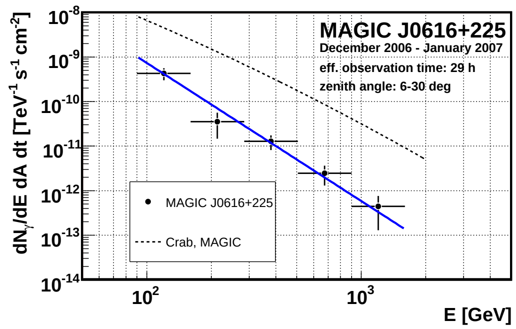

Figure 2: VHE γ-ray spectrum of MAGIC J0616+225 (statistical errors only). The full line shows the result of a simple power law fit to the spectral points taking into account correlations between the spectral points that are introduced by the unfolding procedure. The dashed line shows the spectrum of the Crab nebula as measured by MAGIC [27].

Results

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 VHE γ-ray sky map shows a clear excess centered at (RA, DEC)=($06^{\mathrm{h}}16^{\mathrm{m}}43^{\mathrm{s}}$, +22°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' [27]. 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. The observed excess in the direction of MAGIC J0616+225 has a significance of 5.7σ for $\theta^2 \le 0.05\,\mathrm{deg}^2$ for the period II data set. The period I data showed an excess of about 3σ significance at the same sky position.

For the spectral analysis the excess data from a sky region of maximum angular distance of $\theta^2 = 0.05\,\mathrm{deg}^2$ around the excess center were integrated. Figure 2 shows the reconstructed VHE γ-ray spectrum ($\mathrm{dN}_\gamma/(\mathrm{dE}_\gamma \mathrm{dAdt})$ vs. true E_γ) of MAGIC J0616+225 after correcting (unfolding) for the instrumental energy resolution [28, 29]. 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 ($\chi^2/\mathrm{n.d.f} = 1.1$):$\mathrm{d}N_\gamma/(\mathrm{d}A\mathrm{d}t\mathrm{d}E) = (1.0\pm0.2)\times 10^{-11}(E/0.4\mathrm{TeV})^{-3.1\pm0.3}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}$. 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 [30, 27]. The integral flux of MAGIC J0616+225

1. For a technical description see also http://wwwmagic.mppmu.mpg.de/magic/factsheet/

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 the one in 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.

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, it has a luminosity between 100 GeV and 1 TeV of about 2.7×10^{33} erg s^{-1}.

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 [31], that is at the same location of 3EG J0617+2238. 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 [32], who also provided a review of previous measurements regarding this SNR environment. There is a large amount of molecular mass ($<\sim 10^4$ 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 superposed to the central position of the MAGIC source. Moreover, [2] reported the presence of maser emission from $(l, b) \sim (-171.0, 2.9)$, directly spatially correlated with the MAGIC source, see also [33]. The maser emission is an indication for a shock in a high matter density environment. It is assumed to be collisionally excited by H_2 molecules heated by the shock.

An electronic bremsstrahlung hypothesis for the origin of the EGRET source (e.g., [34]) is difficult to reconcile with the fact that the radio synchrotron, X-rays, and optical emission is concentrated towards the rims 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 [35]). This perhaps indicates that the molecular material, which absorbs the optical radiation, is at the remnant's nearest side. The report by [36] also argues that the molecular mass is located between us and the SNR. Similarly, the recent analysis of XMM observations by [12] 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 [37], 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 [4, 9]. The PWN is now co-located with a high density molecular material region [38], which in addition is excited, as measured by high ratio of $\mathrm{CO}(J = 2-1)/\mathrm{CO}(J = 1-0)$ 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.

In closing, it is to be mentioned that a complete coverage of the X-ray emission from the region was made with XMM [10], 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 μm 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 μm 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 we were able to infer the spectrum of this source 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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