Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 3 (OG part 2), pages 1045–1048

ID 1019

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

Discovery of Very High Energy Gamma-Rays from the Distant Flat Spectrum Radio Quasar 3C 279 with the MAGIC Telescope

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Abstract: The quasar 3C 279 is one of the best-studied flat spectrum radio quasars. It is located at a comparatively large redshift of $z = 0.536$: $E > 100$ GeV observations of such distant sources were until recently impossible both due to the expected steep energy spectrum and the expected attenuation of the γ-rays by the extragalactic background light. Here we present results on the observation of 3C 279 with the MAGIC telescope in early 2006. We report the detection of a significant very high energy γ-ray signal in the MAGIC energy range on the observation night of 2006 February 23.

Introduction

3C 279 (RA=$12^{\mathrm{h}}56^{\mathrm{h}}11.1^{\mathrm{s}}$, Dec=$-5°47^{\mathrm{m}}22^{\mathrm{s}}$) was the first blazar discovered in γ-rays with the *Compton Gamma-Ray Observatory* [1]. It is an exceptionally bright and variable source at various energy bands. In the optical, typical variations of 2^{m} have been observed, while during flares, up to 8^{m} were reached [2]. Variations were observed on day-scale [3], are mostly coherent at all frequencies, and the spectral energy distribution (SED) hardens when the source brightens [4]. Typical flux variations by factors of ~ 20 in the GeV and $\sim 5-10$ in the IR-to-UV have been found [5]. The strongest variability occurs on timescales of a few weeks to ~ 6 months.

Blazars are thought to be supermassive black holes in the centers of galaxies accreting matter. They possess strongly collimated, ultra-relativistic plasma outflows (jets), aligned closely to the observer's line of sight. Thus, their SEDs are almost entirely dominated by the jet emission. In νF_ν representations, they are characterized by two distinct nonthermal components. The lower energy bump is commonly ascribed to synchrotron radiation emitted by relativistic electrons. There is less agreement about the origin of the high-energy bump. In leptonic acceleration models, inverse Compton (IC) scattering of synchrotron (self-synchrotron Compton, SSC, models) or ambient photons (external-inverse Compton, EIC, models) on high energy electrons explain the MeV-to-TeV radiation. While BL Lac objects can often successfully be described by SSC models, the more luminous Flat Spectrum Radio Quasars (FSRQ) usually are modeled requiring external components, particularly in the $E > 100$ keV regime [6], although the existence of EIC components is questioned e.g. by [7, 8, 9].

Since its discovery in γ-rays, 3C 279 was extensively studied, in particular also during various multi-wavelength campaigns [3, 4, 6, 10, 11, 12]. The broadband SED extends from radio frequencies to the γ regime and is, with a comparatively low synchrotron peak, fairly typical of FSRQs. Correlations between the two peaks, which are expected in leptonic models, were partially observed [6], although no consistent patterns were found.

The SED of this source is rather complicated, and in spite of detailed observations, still poorly understood. Observations of the high-energy part of the spectrum are complicated by the fact that terrestrial and satellite-borne instruments together can, at present, not fully cover the frequency range of the high-energy bump. Additionally, the very high energy (VHE, defined by $E > 100$ GeV) spectrum is in part suppressed from interactions with the extragalactic background light (EBL). This modification is, of course, strongly dependent on the source distance. Thus, distant VHE γ-ray sources represent an excellent tool for determining the 0.3 to 30 μm EBL (e.g., [13]), which at redshift $z = 0$ was observed by various satellite experiments, although direct measurements suffer from huge foreground contaminations by light contributions from the solar system and our galaxy. As of now, several different EBL models have been proposed [13, 14, 15]. A precise measurement of the energy spectrum of 3C 279 is crucial for two reasons: With a state-of-the-art EBL model, emission models for 3C 279 can be tested in detail. By using conservative arguments on particle acceleration mechanisms, the γ-ray emission of 3C 279 also permits to formulate stringent constraints on the EBL level.

All extragalactic VHE γ-ray sources detected so far are of the BL Lac type. These objects are the low-luminosity counterparts of the FSRQ class of AGNs [16], with their synchrotron peaks shifted to higher energies [17]. BL Lac objects have been detected aplenty recently in the VHE range: 17 BL Lacs have been found so far,[1] reaching to redshifts of $z = 0.212$ [18], plus M87, assumed to be a misaligned BL Lac. The sample includes also blazars as PG 1553+113 [19] with its extremely soft energy spectrum and recently discovered BL Lacertae itself [20], which is the first "low-peaked BL Lac object" ($\nu_{\mathrm{synchr}} < 10^{14}$ Hz). Both observations were largely made possible from the exceptionally low energy threshold of the MAGIC telescope.

In January 2006, 3C 279 was found in a high optical state, brightening to $14^{\mathrm{m}}5$ in the R-band.[2] A WEBT campaign in early 2006 [12, 21] and multi-wavelength campaigns during both periods [11] were performed in order to get further information on the temporal and spectral properties of 3C 279.

Up to recently, a VHE γ-ray detection of 3C 279 was prevented by its high redshift of $z = 0.536$. The resulting cutoff due to EBL attenuation is expected at around $E \approx 200$ GeV. The MAGIC (Major Atmospheric Gamma-ray Imaging Cerenkov) telescope [22] is currently the largest single-dish (17 m diameter) Imaging Atmospheric Cerenkov Telescope, located on the Canary Island of La Palma. With its low trigger threshold ($50-60$ GeV at low zenith angles) is best suited for observing the lower part of the VHE range of distant AGN spectra. At the geographical latitude of MAGIC ($28°45'$ N), 3C 279 can be observed under medium zenith angles (above 34°), with an accordingly increased observation threshold.

Observations and Analysis

3C 279 was observed from late January to April 2006 and in January 2007. Simultaneous optical R-band observations were carried out using the 1.03 m telescope at the Tuorla Observatory, Finland, and the 35 cm KVA telescope on La Palma. Here we report results from the 2006 observations.

The VHE γ-ray observations were performed in the ON-OFF mode. ON data were collected while pointing directly to the source, while OFF data, necessary for the background estimation, were recorded by pointing to a nearby region of the sky. The OFF region, in which no γ-ray source is expected, was chosen to have a comparable zenith angle distribution and night sky conditions. From 2006 January 29 to 2006 April 4, 3C 279 was observed for 14.9 hours. In addition, 3.9 hours of OFF data were recorded. Data taken during non-optimal weather conditions or affected by hardware problems were excluded from the analysis. This concerned 5.2 hours worth of ON data. The remaining events were calibrated [23] and analyzed using the standard MAGIC analysis chain [24, 25]. Briefly, the analysis proceeds by reducing the image to a single light cluster by removing noise, calculating image parameters [26], and using a multi-variate method to discriminate γ-like

1. See http://www.mppmu.mpg.de/~rwagner/sources/ for an up-to-date list

2. Long-term optical monitoring data are available at http://users.utu.fi/kani/1m/

events from the dominant hadronic background. For the latter step, we use the Random Forest (RF) method [27], which combines the image parameters into a single test statistic, called hadronness, based on training samples of both Monte Carlo generated γ [28, 29] and real background events. The excess events were identified using the classical ALPHA approach by subtracting suitably normalized OFF data from the ON events. The significance of any excess was calculated according to Eq. 17 in [30]. The energy estimation for each event was performed using a RF method, too, leading to a reasonably constant energy resolution of ≈23% above 150 GeV.

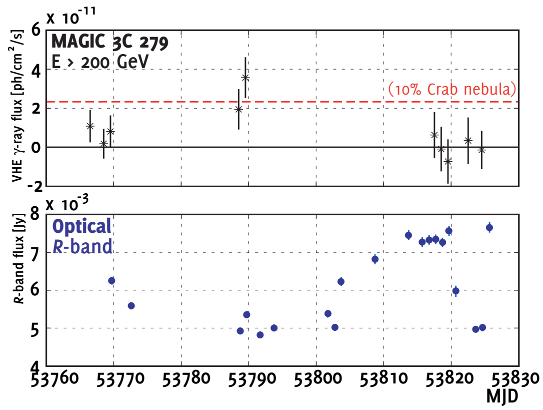

Figure 1: MAGIC $E > 200$ GeV γ-ray (top) and optical R-band (bottom) light curves obtained for 3C 279 in early 2006.

Results

The data were subjected to three independent analysis chains, which obtain compatible results w.r.t. each other. A standard analysis with an energy threshold of $\approx$ 200 GeV was used to infer the $E > 200$ GeV light curve given in Figure 1. Also shown is a R-band optical light curve for ten MAGIC observation nights from 2006 January 31 to 2006 March 31. The typical observation time per night is around one hour. While in most of the nights γ-ray fluxes compatible with zero were observed, during the 2006 February 22 observations a marginal signal was seen. In the night of 2006 February 23 we found a clear γ-ray signal with an integrated photon flux $F(E > 200\,\mathrm{GeV}) = (3.5 \pm 0.8) \times 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The source was observed for 62 minutes (MJD 53789.1633−53789.2064) at zenith angles between 35° and 38°. The stable event rate during this observation allows classifying it as "dark night" rate, although minimal moonshine was present.

A low-energy analysis, exploiting the timing properties of the air shower images with a lower analysis threshold, $\approx$ 110 GeV, was used to calculate the significance of the found excess. Threshold is defined as the maximum of the energy distribution of the accepted events, *viz.* showers with energies down to $\approx$ 80 GeV are included in the sample. Both analyses show consistent results from $E \geq 200$ GeV on. After subjecting the ON data to an ALPHA cut inferred from training on an (independent) Crab nebula data sample recorded at similar zenith angles, and subtracting a properly normalized OFF distribution in the signal region, 624 and 93 excess events remain between 80 and 220 GeV and between 220 and 600 GeV, respectively (Fig. 2). The data were separated into these two independent samples because of the very different γ/hadron separation powers in the two energy regions: Adding the highly-enriched, low statistics high-energy γ sample to the large statistics low-energy sample would spoil the overall significance calculation. The resulting significances are 6.1σ in the low energy region and 5.1σ in the high energy region; the excess is compatible with a point-like source and its position is consistent, within statistical uncertainties, with the 3C 279 position. The signal at low energies exceeds the intensity of the Crab nebula, while for $E > 200$ GeV it is ≈15% of the Crab nebula flux. The spectral analysis of the data is ongoing. Our γ-ray detection was not accompanied by an optical flare or by particularly high flux levels or outbursts in X-rays [31, 32].

Conclusions

In observations triggered by a high optical state of the flat spectrum radio quasar 3C 279, MAGIC was able to detect a highly significant VHE γ-ray signal from this source, well-known and much studied at lower energies. This discovery is a crucial step forward for VHE γ-ray astronomy in various contexts:

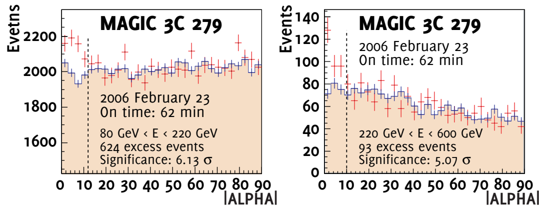

Figure 2: The γ-ray signal below (left) and above (right) 220 GeV on 2006 February 23. Showers which are aligned parallel to the telescope axis have small ALPHA values. To remove residual hadronic background, OFF data were normalized to the ON distribution between $20^\circ < \mathrm{ALPHA} < 80^\circ$ and subtracted from it. The structure visible in the left ALPHA plot in the OFF data is statistically compatible with a flat distribution.

- The distance over which astrophysical objects can be observed at VHE γ-ray energies was enlarged substantially—when the photons recorded during our observations left 3C 279, the age of the Universe was only 8.4 Gyr.
- For the first time, VHE γ-rays from a flat spectrum radio quasar were detected. These objects are very luminous, but are not expected to show intense $E > 100$ GeV emission. With 3C 279 and BL Lacertae, objects of all classes comprising the "blazar sequence" [17] have now been detected in VHE γ-rays.
- A precise measurement of the energy spectrum in the VHE region may allow for stringent constraints on the EBL density.

Acknowledgments

We thank the IAC for the excellent working conditions in La Palma. The support of the German BMBF and MPG, the Italian INFN and Spanish CICYT is gratefully acknowledged. This work was also supported by ETH Research Grant TH 34/04 3 and by the Polish MNil Grant 1P03D01028. Further we are grateful to the RXTE-ASM and Swift/BAT teams for providing their X-ray monitoring data and in particular to Hans Krimm for quickly analyzing the 2006 February 23 BAT data.

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