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Observation of the SNR Cassiopeia A with the MAGIC telescope

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Abstract: The Supernova remnant Cassiopeia A was observed with the MAGIC telescope for about 50 hours in winter 2006/07. The observations were performed in the so-called wobble mode, under moderated Moon illumination. Above 1 TeV, Cas A very high emission detecion was claimed by the HEGRA Stereoscopic Cherenkov Telescope System, at the level of few percent of Crab. The detection of TeV gamma-rays proves that Cas A is a site of CR acceleration for particles - either nucleons or electrons - with multi-TeV energies. MAGIC has confirmed the detecion at 5.2σ level. The spectrum is well described with a power-law with differential flux at 1 TeV, dN / (dE dA dt) = (1.0$\pm$0.1$_{stat}$$\pm$0.3$_{sys}$ $\times$ 10^{-12})$TeV^{-1}cm^{-2}s^{-1}$ with photon index of Γ=2.37$\pm$0.27$_{stat}$ and extends to a lower energy around 250 GeV. Further results will be presented.

Introduction

Cassiopeia A (Cas A) is a shell type supernova remnant (SNR) and a bright source of synchrotron radiation observed at radio frequencies [1], [2], and also in the X-ray band [3], [4] (See also the online Green Catalogue of Galactic SNRs [5]). Its distance is estimated to be 3.4 Kpc by [6]. The remnant is seen as a patchy and irregular shell with a diameter of 4' (4 pc at 3.4 Kpc) in optical, X-ray and IR wavelength. The existence of a central object was revealed from the high resolution X-ray images taken by Chandra satellite [7]. The SNR results from the explosion of the latest known Galactic supernova, exploded in 1680. The progenitor of Cas A was a Wolf-Rayet star [8], with an initial mass between 15 and 25 $M_\odot$ [9]. Nuclear decay lines are detected from ^{44}Sc and ^{44}Ca [10], [11]. These are the daughter nuclei of ^{44}Ti, which is produced in a core collapsed SN explosion [12]. The supernova blast waves expand into a wind bubble which is formed from the previous wind phases of the progenitor star. The Cas A environment influences strongly the particle acceleration process at the SNR site [13].

The HEGRA Stereoscopic Cherenkov Telescope System detected Cas A in TeV energies at 5σ level, within 232 hours observation time from 1997 to 1999. Above 1 TeV the total flux derived was (5.8 $\pm$ 1.2$_{stat}$$\pm$1.2$_{syst}$) 10^{-13} ph cm^{-2}s^{-1} [14]. The spectral distribution was consistent with a power law with a differential spectral index of -2.5$\pm$0.4$_{stat}$$\pm$0.1$_{syst}$ above 1 TeV. The results were consistent with the upper limits set by Whipple [15] and CAT [16] at TeV energies.

In this work we study the very high energy γ-ray emission from the SNR at lower energies than HEGRA, with an aim to distinguish between leptonic and hadronic models for the origin of the emission.

Analysis and Results

The MAGIC (Major Atmospheric Gamma Imaging Cherenkov) Telescope is located on the Canary

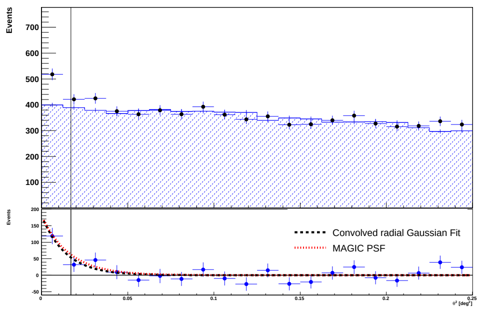

Figure 1: *Distributions of θ^2 (in degrees). In the lower panel shows the θ^2 distribution after background subtraction. The excess number is obtained for events with θ^2 below a selection cut (vertical line). The red Gaussian curve is the telescope PSF. The black curve is the result of a Gaussian fit and limits the extension of the source.*

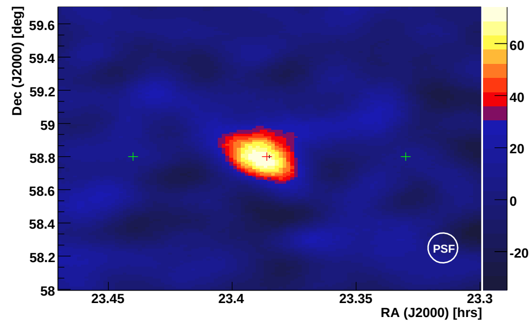

Figure 2: *Sky Map of Cas A region. A cut in SIZE of 400 p.e. was applied: the green crosses are the 2 wobble positions; the black cross is the HEGRA c.o.g.; the red cross is the MAGIC c.o.g.*

Island La Palma (2200 m asl, $28°45'N$, $17°54'W$). It has a 17m-diameter tessellated reflector dish and a 3.5° field of view camera that comprises 576 photomultipliers (PMTs). The accessible energy range spans from 50-60 GeV (trigger threshold at small zenith angle) up to tens of TeV. The γ-ray point spread function is about 0.1°. Another important feature of MAGIC is its capability to observe under moderate Moon light [17].

We observed Cas A between June 2006 and January 2007. After quality cuts the total exposure was 47 hours. The zenith angle ranges from 29° to 45° with an average of 35°. The observation was done in the so-called wobble mode [18], in which two opposite sky positions at 0.4° off the source are pointed in intervals of 20 minutes. A fraction of 86% of the data were taken under moderated Moon light illumination. Anode currents of photomultipliers vary between 1 and 6 μA, due of the Moon light illumination (being 1 μA the anode current for dark observations). The trigger discriminator threshold (DT) was accordingly modified to keep a low accidental trigger rate. The DT level affects the relative γ-ray detection efficiency, decreasing to 0.84 times the efficiency for dark observations, as well as the relative sensitivity, which went to 2.7% of Crab (for dark observation it is 2.5 %). The energy threshold rise ($\approx$ 5 GeV) is negligible compared to the rise induced by the intermediate zenith angle observations. Therefore the effects of the moderate Moon light illumination did not reduce substantially the telescope performances.

We analyzed dark and moon data using standard analysis and calibration programs of the MAGIC collaboration [19], [20], [21]. For the cleaning of images absolute tail and boundary cuts of 10 and 5 photoelectrons (p.e.) were used respectively. For γ/hadron separation, the shower images were parameterized using the Hillas parameters [22], and the Random Forest (RF) classification algorithm was used. The RF was trained with a sample of pure γ-ray showers (MC) [23], and a sample of hadron showers (OFF data).

The distribution of θ^2 values is shown in Figure 1, where θ is the angular distance between the source position in the sky and the reconstructed arrival position of the air shower. The later position is determined for each shower image by means of the so-called DISP method [24]. In order to determine anti-sources, five symmetrically distributed regions are chosen for each wobble position w.r.t the camera center. Dark Crab data in the same observation conditions of Cas A were used to get an optimum HADRONESS and angular cut. The lower size cut is 400 p.e where the MAGIC signal to noise ratio optimizes. The on source events histogram is shown with black points while the off events one in blue shaded. The subtraction of the later from the former shows the excess in the direction of Cas A. The excess N_{excess}=157 leads to a significance of 5.2 σ (using the likelihood method of [25]) in the region bellow 0.13°.

Figure 2 shows a background subtracted distribution of reconstructed shower origin centered at the position of Cas A with a lower size cut of 400 p.e. The map is smoothened with a Gaussian of σ=0.07^o. By fitting the non-smoothened sky map to a bi-dimensional Gaussian function, the source position is found to be at RA = 23.386$\pm$0.003$_{stat}$$\pm$0.001$_{sys}$ h and DEC = 58.81$\pm$0.03$_{stat}$$\pm$0.02$^{\circ}_{sys}$.

The X-rays and radio diameter of Cas A is 0.08°, which is close to the MAGIC angular resolution. The MAGIC PSF is σ_{psf}=0.090$\pm$0.002°. This value was obtained with MC simulations and validated with experimental data (Mkn 421 and Crab Nebula data). The events excess was fitted with a Gaussian function convolved with the PSF (F=$P_1 + P_2 exp(-0.5\ \theta^2/(\sigma_{src}^2 + \sigma_{psf}^2))$. The obtained source extension σ_{src} is consistent with a point like source. In Figure 1 the telescope PSF and the result of the Gaussian fit are shown.

Figure 3 shows the measured differential energy spectrum. It is well described with a power-law with differential flux at 1 TeV, dN / (dE dA dt) = (1.0$\pm$0.1$_{stat}$$\pm$0.3$_{sys}$ $\times 10^{-12}) TeV^{-1} cm^{-2} s^{-1}$ and a photon index of Γ=2.37$\pm$0.27$_{stat}$. The spectrum was unfolded using a χ^2 minimization by Gauss-Newton method, [26], with a χ^2/d.o.f of 2.83/3. The systematic error is dominated by the uncertainty in the absolute energy determination and is 30%. For energies above 1 TeV the MAGIC results are consistent with the previous of HEGRA.

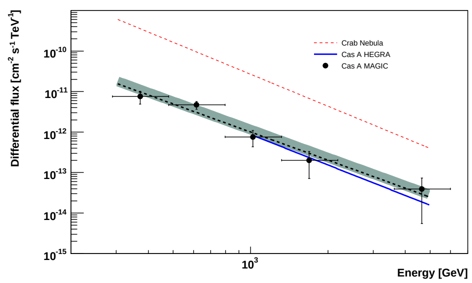

Figure 3: *Cas A spectrum above 250 GeV. The blue line represents the earlier measurement by HEGRA. The red line represents the Crab nebula spectrum. The shaded area is the 1σ statistical error of the fit.*

Discussion

The supernova remnant Cas A was detected above 5 standard deviations by the MAGIC telescope. With these results we confirm the previous detection obtained with the HEGRA. Furthermore the MAGIC observations provide spectral information down to 250 GeV. The differential energy spectrum can be well described by a simple power-law. No cut-off at high energies could be found. The very high energy γ emission from Cas A is an evidence of acceleration of charged particles (electrons or nuclei) at the supernova remnant site, up to multi-TeV energies. Our results were compared to two detailed models of very high energy γ-ray emission from Cas A. The first model considered is described in [27]. A multi-zone model was used in order to fit the observations in the radio band, and to understand the propagation of relativistic electron in the remnant. The model has magnetic field in the various regions around and below 1mG. The TeV γ ray emission originated by these electrons via Inverse Compton scattering and bremsstrahlung has steep cut-off for multi-TeV energies, which is not seen in the MAGIC results. The same model considers also TeV γ-ray production by means of proton interaction and π_0 decay. Pion produced γ ray would have an hard energy spectrum up to 1 TeV. Also this feature is not seen although the error on the photon index is too large in order to get a definite conclusion.

The second model considered is described in [13]. The model does not focus on the effects of small scale inhomogeneities, as the previous one. It considers the whole supernova remnant blast wave as main particle accelerator. The leptonic and the hadronic emission which are predicted by the model are shown in fig 4. The hadronic emission is calculated with and without a cut-off at 4 TeV. The photon index of the predicted γ-ray emission is hard in the energy range of interest, i.e. between few hundred of GeV to few TeV. This photon index is perhaps too hard in order to give a good fit of the MAGIC data. Also in this model the normalization of nucleonic prediction of gamma ray is to

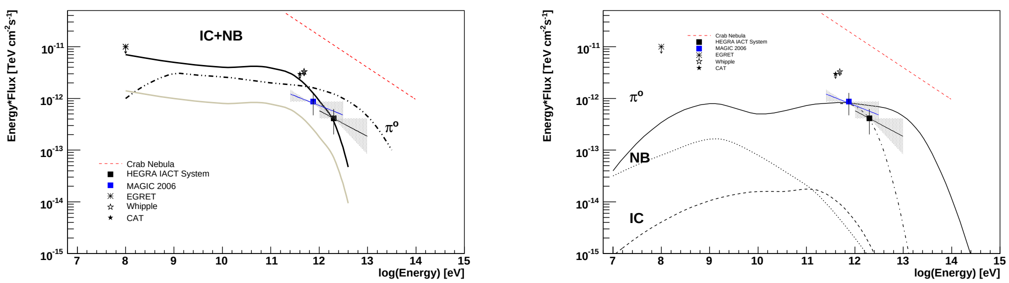

Figure 4: *Cas A spectrum energy distribution as measured by MAGIC. The shaded area is the 1σ statistical error range, under the assumption of power law spectrum. Whipple, EGRET and CAT upper limits and the HEGRA spectrum are also indicated. On the left, the MAGIC and HEGRA spectra compared with the model in [27]. Gamma-ray fluxes from Inverse Compton (IC) plus nonthermal Bremsstrahlung (NB) for different model parameters are shown with black and grey solid lines. The π^o-decay (dotted) γ-ray energy flux is shown with dotted-dash line. On the right, the MAGIC and HEGRA spectra are compared with the model in [13]. Both, hadronic and leptonic γ-ray emission are shown*

be considered a free parameter, within reasonable boundaries.

In general the measurement of the differential energy spectrum of very high energy γ rays from Cas A should be extended at lower and higher energies in order to better constrain the existing models. Also a better signal-to-noise ratio is needed, to have a better determination of the spectrum of this weak source.

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