

Observation of selected SNRs with the MAGIC Cherenkov Telescope

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Abstract. Supernova Remnants (SNRs) are believed to be the acceleration sites of galactic cosmic rays. As such they are expected to produce Very High Energy (VHE) gamma-rays through hadronic and/or electromagnetic scenarios, hence they are natural targets for observations with ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs). Currently, VHE emission has been detected from several SNRs, making them one of the most abundant types of established galactic VHE sources. The MAGIC telescope, located in the Canary island of La Palma, has been performing observations of several SNRs over the last two years. Parameters like age, distance, radio flux, or possible EGRET association (i.e., criteria matching those already used for previous successful IACT SNR detections), were used to select candidate targets. Here we summarize the results of the past two years of observations.

Keywords: Supernova Remnants, VHE gamma-rays

I. INTRODUCTION

It has been believed for long time that supernova (SN) explosions and their remnants (SNRs) are the places where the acceleration of galactic cosmic rays takes place. Energetic arguments as well as the diffuse shock acceleration mechanism applied to young SNRs support this idea. A SN explosion every 30 years is enough to balance the escape losses of cosmic rays in the Galaxy.

During the past years, IACTs have confirmed that SNRs are sources of VHE gamma-rays. Two scenarios can explain the production of the gamma-rays. In the electromagnetic scenario, accelerated electrons can up-scatter low energy photons through the inverse Compton mechanism. In the hadronic scenario, accelerated nuclei can interact with matter or radiation producing neutral mesons that will decay into gamma-rays.

A. The MAGIC telescope

MAGIC (*Major Atmospheric Gamma-ray Imaging Cherenkov*) is a ground based gamma-ray telescope

located on the Canary island of La Palma¹. It is a new generation IACT with a trigger threshold of 55 GeV, and an energy detection range from 60 GeV to 10 TeV, overlapping with the upper energy threshold of satellites such as Fermi. The design of the MAGIC telescope was a technological challenge which took the existing technology to its limit [1], [2]. One of its main characteristics is its octagonal parabolic reflector of 17 m of diameter resulting in an area of 240 m², capable of obtaining three times more light than a conventional IACT of 10 m. For energies above 150 GeV, the telescope angular and energy resolutions are $\sim 0.1^\circ$ and $\sim 25\%$ respectively [3]. Besides this, in April 2007 its data acquisition system was upgraded with multiplexed 2 GHz FADCs which improved the timing resolution of the recorded shower images. Accordingly, the integral sensitivity of MAGIC improved significantly from 2.2% to 1.6% of the Crab Nebula flux above 270 GeV for 50 hours of observation [4].

The MAGIC collaboration has finished the construction of a second telescope, MAGIC-II, similar to MAGIC with improved technology. Located at a distance of eighty five metres from the first telescope, it will be fully operational in the second half of 2009. The operation of both telescopes in stereoscopic mode will allow us to improve the spatial resolution and sensitivity of the MAGIC experiment.

II. SNRS OBSERVED BY MAGIC

During 2007 and 2008 the MAGIC telescope has performed observations of different SNRs. The data include a deep observation of the Tycho SNR and shorter observations of various radio selected SNRs.

A. Tycho SNR (G120.1+1.4)

The Tycho SNR is one of the best known and most studied SNRs. It is a shell-type SNR (well defined in radio and X-Ray) which was formed from, most likely, a Ia supernova explosion in 1572. This young SNR is a bright X-ray source with a similar diameter of 8' in both X-rays and radio. The spatial structure of Tycho has

¹The MAGIC telescope is operated on the island of La Palma by the MAGIC Collaboration in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias

been studied by Chandra and XMM-Newton, providing constraints to the allowed explosion models. Although the age of the SNR is known with precision, the distance is not well known. Distance estimates vary between 2.2 kpc [5] and 4.4 kpc [6]. Most accepted values are in the range 2.3-2.8 kpc. However, recent measurements based on the light echo [7] suggest that a larger distance of 3.8 kpc could also be possible.

VHE gamma-ray emission from Tycho is predicted by the non linear kinetic theory of Cosmic Ray acceleration in SNRs [8] [9]. In such models, the dominating mechanism for gamma-ray emission is π^0 decay rather than inverse Compton. However, spatial correlations in various SNRs between hard X-rays and VHE gamma-rays favour the idea that energetic electrons are responsible for the gamma-ray emission [10], [11]. The detection of VHE gamma-rays from the Tycho SNR above several TeVs would help to clarify the nature of the mechanism responsible for the VHE gamma-ray emission.

Tycho has been observed at VHE gamma-rays by the Whipple [12] telescope and the HEGRA telescope array [13], however none of them found VHE gamma-ray emission. In the case of HEGRA, a search for TeV gamma-radiation from Tycho SNR was performed over 2 years (1997/98). No evidence for such emission was found and a 3σ level upper limit was estimated: 3.3% Crab at 1 TeV (5.79×10^{-13} ph cm $^{-2}$ s $^{-1}$).

B. Radio Selected SNRs

The Green Catalog of SNRs [14] contains 265 Galactic SNRs plus some possible candidates. It includes information about the flux and spectral index at 1 GHz, summarizing the information scattered over hundreds of publications and catalogs. This information has been used to select a list of SNRs whose parameters are similar to those of 6 well identified SNRs that are also known to be VHE gamma-ray emitters: IC443, RXJ0852-4622, RCW86, RXJ1713-3946, W28 and Cas A. From the known SNRs with VHE emission, we defined the following selection criteria² to find targets for our observations:

- **Flux at 1 GHz ≥ 49 Jy**
- **Radio Spectral Index ($S_\nu \propto \nu^{-\alpha}$) ≤ 0.6**
- **Distance ≤ 7 kpc**
- **Age ≤ 50000 yr**

From all the sources contained in the Green Catalog, a total of 37 candidates met the selection criteria. Only 25 of these sources are observable by MAGIC with a zenith angle below 50° . From these 25 sources some were removed because they have already been detected in gamma-rays (Crab, IC443, ...), were previously observed (Tycho) or were covered by the H.E.S.S. galactic scans. Finally we selected the 9 sources shown in table I as interesting targets to perform observations with MAGIC.

²Some of the parameters are unknown or have large uncertainties. The selection criteria are not a strict rule for selection but a guideline.

TABLE I
PARAMETERS OF THE SELECTED SNRS.

Source	Diameter (arcmin)	Distance (kpc)	Age (10^3 yr)	Flux 1 GHz (Jy)	Radio Spec. Index
HB-9	130	1	7.7	110	0.6
W51	30	6	30	160	0.3
CTB-80	80	2	100^2	120	–
W63	80	1.6	–	120	0.5
W66	60	1.5	50	340	0.5
HB-21	105	0.8	19	220	0.4
G85.4+0.7	24	3.8	6.3	–	0.5
G85.9-0.6	24	5	4	–	0.5
CTB-104 A	80	1.5	–	65	0.4

III. OBSERVATIONS AND RESULTS

All observations were performed in false-source tracking mode, named Wobble mode [15], with two directions at a distance of $24'$ and opposite sides of the source position. This technique allows for a reliable estimation of the background with no need of extra observation time.

Data analysis was carried out using the standard MAGIC analysis and reconstruction software chain, which proceeds in several steps: calibration [16], image cleaning procedure [4] and parametrization with Hillas parameters [17]. The signal-to-noise maximization is achieved using a multidimensional classification procedure based on the Random Forest method [18], where a hadron likeness measure (*hadronness*) is computed for each event based on the image and time parameters. A sky map has been obtained for events surviving a *hadronness* cut, to search for signal in the field of view around the source. We have also obtained upper limits to the VHE flux for all sources when no positive detection was found. These upper limits have been computed using the Rolke method [19] at a 95% confidence level and they take into account a 30% of systematic uncertainties in the flux level.

A. Tycho SNR

MAGIC observations of Tycho were performed between July and November 2007. The zenith angle of the observations ranged between 35° and 50° . Part of the data were taken under moderate moonlight conditions (40%). The total observation time is 69.4 hours after quality cuts (mainly rejection of bad weather runs). During moonlight observations the trigger discriminator threshold varied between 15 and 25 arbitrary units to keep a low rate of accidental triggers. The effect of the higher discriminator threshold is negligible compared to the rise due to the medium to high zenith angle. Dark and Moon data are analyzed together using the standard MAGIC analysis. The recorded images were cleaned using time image cleaning with boundary cuts of 8 and 4 photoelectrons (typical values for Dark observations are 6 and 3). The $8'$ diameter of the Tycho SNR is very close to the angular resolution of MAGIC ($6'$), so the source is very close to point-like for MAGIC.

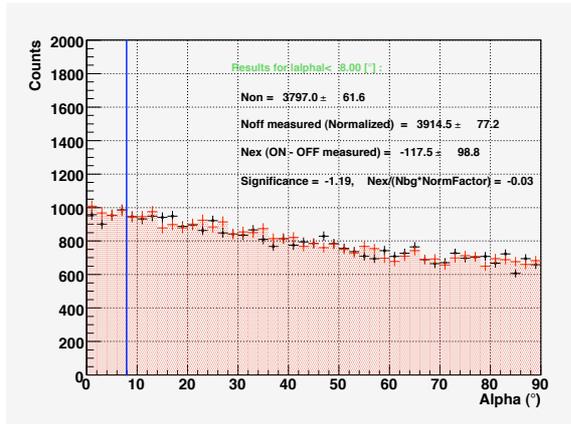


Fig. 1. Alpha distribution

The so-called α distribution for the source and the anti-source positions are shown in Figure 1 for an energy threshold of 350 GeV (Size cut of 300 and reconstructed energy cut 300 GeV).

No positive evidence for VHE gamma-ray emission from Tycho was found. For an energy threshold of 350 GeV we obtain an integral upper limit (3σ) for point-like source emission (valid hypothesis for Tycho, given its size) of 1.86×10^{-12} ph cm⁻² s⁻¹, which corresponds to $\sim 2\%$ of the Crab spectrum at the same energy. For an energy threshold of 1 TeV the corresponding integral upper limit (3σ) is 2.95×10^{-13} ph cm⁻² s⁻¹ ($\sim 1.7\%$ Crab), 50% better than that obtained by the HEGRA telescope array. With a confidence level of 2σ the corresponding upper limits at 350 GeV and 1 TeV are respectively 7.04×10^{-13} ph cm⁻² s⁻¹ ($\sim 0.7\%$ Crab) and 1.16×10^{-13} ph cm⁻² s⁻¹ ($\sim 0.7\%$ Crab).

B. Radio selected SNRs

All selected sources were observed for a time varying between ~ 5 and ~ 10 hours, depending on the SNR. Although this time is clearly small (specially for extended sources and off-axis) it could trigger deeper observations in case that a signal hint was found. Table II shows some details of the observations: central position of the observations (not always the center of the SNR), date of the observations and effective time after quality cuts (bad weather rejection). The observations were done under Moon conditions. Only W66 (γ -Cygni) was observed under Dark conditions. The images were cleaned using time image cleaning with boundary cuts of 8 and 4 photoelectrons for the Moon observations and 6 and 3 photoelectrons for the Dark observations of W66.

Assuming a conservative sensitivity of 2% Crab (5σ , 50 hours) for the Crab Nebula spectrum, we can expect to find a point like source at 5σ level in ~ 8 hours for a 5% Crab flux or in ~ 2 hours for a 10% Crab flux, if the source was point-like and located at the center of the two wobbling positions used in each observation. The small trigger area of MAGIC ($\sim 0.9^\circ$ diameter) makes things more difficult when the source is not located at the center

of the observations or when the source is extended. For a point-like source located 0.5° from the center of the observations the times needed for a 5% Crab flux and a 10% Crab detection at 5σ level would be ~ 30 hours and ~ 8 hours respectively.

TABLE II
SOME PARAMETERS OF THE OBSERVATIONS PERFORMED ON THE 9 RADIO SELECTED SNRS. ALL OBSERVATIONS ARE DONE IN WOBBLE MODE IN MOON TIME, EXCEPT W66.

Source	RA (h)	DEC ($^\circ$)	Date (Month/Year)	Eff. Time (h)
HB-9	5.02	+46.67	08-09/08	6.35
W51	19.40	+14.51	07-08/08	7.38
CTB-80	19.89	+32.88	07-09/08	5.06
W63	20.32	+45.7	11-12/08	5.36
W66	20.36	+40.26	06-09-11/08	11.4
HB-21	20.75	+50.6	08-09-11/08	7.90
G085.4+0.7	20.85	+45.37	06-07/08	5.21
G085.9-0.6	20.98	+44.9	06-07/08	6.28
CTB-104 A	21.49	+50.8	07-08/08	7.97

After analysis of all sources, we found no significant ($> 5\sigma$) gamma-ray emission from any of them. We have obtained integral upper limits for the VHE flux coming from a point-like source located at the center of the wobble observations. The corresponding integral upper limits (3σ) above an energy threshold of 270 GeV are shown in table III.

TABLE III
UPPER LIMITS FOR A POINT-LIKE SOURCE LOCATED AT THE CENTER OF THE OBSERVATIONS (NOT NECESSARILY THE CENTER OF THE SNR) FOR ENERGIES ABOVE 270 GeV.

Source	Integral Flux UL (ph cm ⁻² s ⁻¹)	Flux U.L. Crab units
HB-9	1.60×10^{-11}	11%
W51	1.26×10^{-11}	9%
CTB-80	3.56×10^{-11}	25%
W63	3.36×10^{-11}	24%
W66	6.68×10^{-12}	5%
HB-21	7.88×10^{-12}	6%
G085.4+0.7	2.58×10^{-11}	18%
G085.9-0.6	2.10×10^{-11}	15%
CTB-104 A	1.40×10^{-11}	10%

The skymaps obtained for every source are shown in figure 2 where no significant point-like gamma-ray excess has been found. For extended sources, the significance is reduced in our observations because of the small trigger area of MAGIC which makes difficult the detection of sources of various tenths of degree. In the case of W51, the recently reported VHE emission from J1923.0+1411 by MILAGRO [20] is coincident with an area of higher significance in the rim of the shell (see Figure 2). H.E.S.S. reported [21] a 3% Crab flux from this source which is well below our upper limit (9% Crab). The small observation time (7.4 hours), the size of the source and its low flux made it not possible to have a significant signal in our observations and only a hint of the source can be seen as the $\sim 3\sigma$ significance area in the skymap.

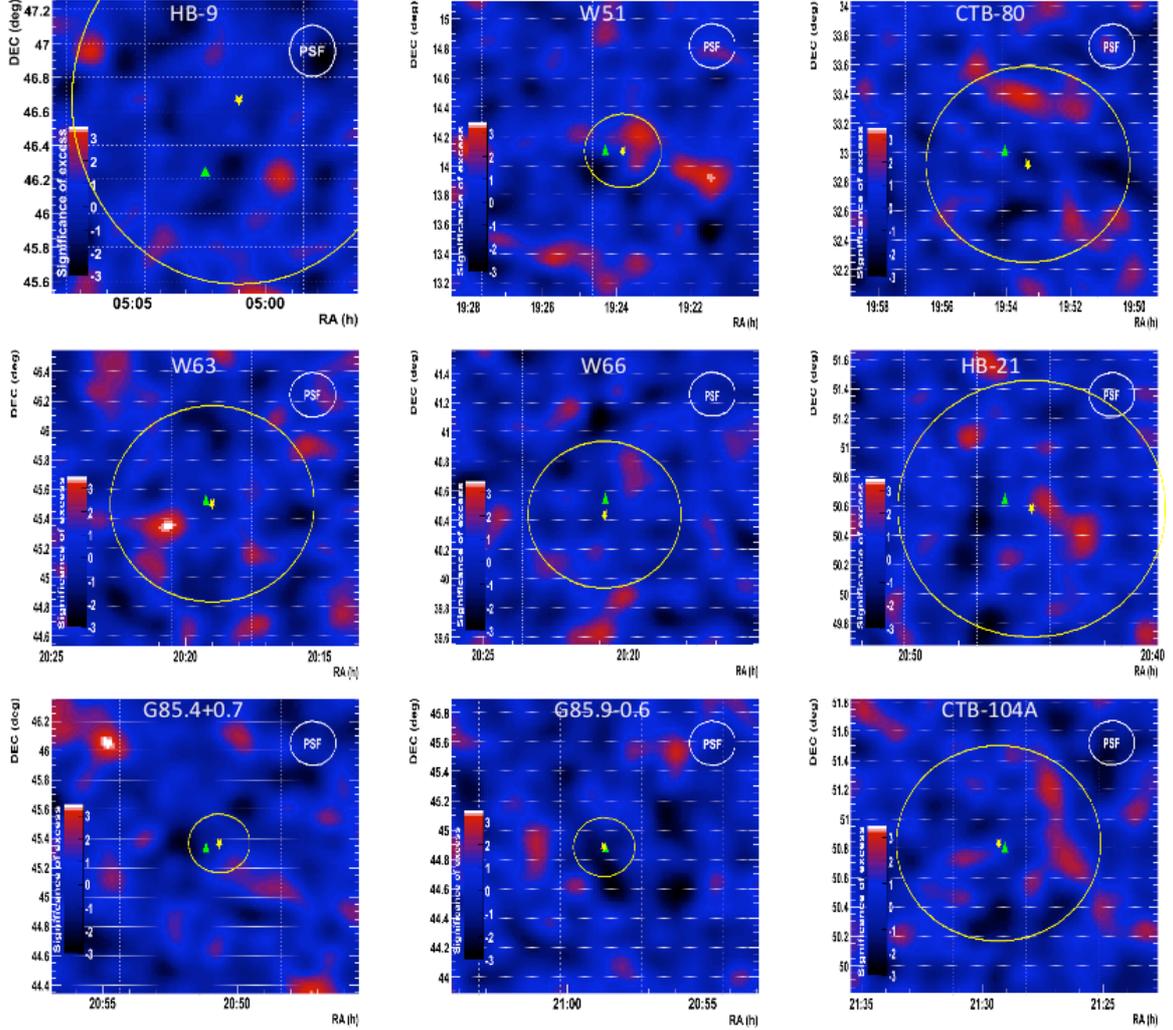


Fig. 2. Skymaps of all 9 radio selected SNRs. The yellow star marks the center of the SNR and the circle is the approximate boundary of the radio shell (data from the Green Catalog). The green triangle marks the center of the wobble observations. Starting from top-left and to the right: HB-9, W51, CTB-80, W63, W66, HB-21, G085.4+0.7, G085.9-0.6 and CTB-104 A.

IV. CONCLUSIONS

No significant VHE gamma-ray emission has been found for Tycho and the radio selected SNRs. In the case of Tycho, VHE gamma-ray emission is predicted at a level that should have been detected in our observations if the distance is below ~ 3.5 kpc. The distance to the SNR is still uncertain although most measurements lie below 3.6 kpc. Our result may indicate that the distance could be larger than it is usually believed. In the case of the radio selected SNRs, the computed upper limits range from 5% to 25% Crab, assuming a point-like source at the center of the observations. In addition, the skymaps show no significant ($> 5\sigma$) evidence of VHE emission coming from point-like or small size sources located inside the shell of the SNRs.

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