Proceedings of ICRC 2001: 2461 © Copernicus Gesellschaft 2001

ICRC 2001

Observations of the Monoceros SNR/Rosette nebula interacting region with the HEGRA system of IACTs

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Abstract. The array of 5 imaging atmospheric Čerenkov telescopes (IACTs) deployed at La Palma of Canary Island, and operated by the HEGRA (High Energy Gamma Ray Astronomy) collaboration, was used for the observations of the interaction region of the Monoceros SNR with the dense Rosette nebula for a total of about 120 hrs and 20 hrs in ON-source and OFF-source mode, respectively. At present the performance of the IACTs array reveals the energy threshold of 500 GeV and the angular resolution of $0.1°$ for γ-rays. Using the HEGRA system of IACTs of rather large field of view (4.3 degree in diameter), we have mapped the extended sky region of $2° \times 2°$ associated with the Monoceros SNR/Rosette nebula and which is centered towards the hard spectrum X-ray point source SAX J0635+533. The EGRET unidentified source of diffuse γ-ray emission (3EG J0634+0521) observed in the energy range between 100 MeV - 10 GeV, was effectively in the field of view of our present observations. Based on the Monte Carlo simulations and real data we have studied the response of the IACTs array over its $5 \cdot 10^{-3}$ str field of view with respect to the cosmic rays and diffuse γ-ray emission. We have derived a normalization function which takes into account the slightly non uniform sensitivity to the γ-ray fluxes (with the variation of $\leqslant 10\%$) within the angular distance of 1 deg from the joint optical axis of the telescopes' array after the analysis by mean scaled Width.
Here we present the result of the data analysis and its physical interpretation.

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1 Introduction

The origin of cosmic rays with energies $E \leqslant 10^{15}$ eV, the so-called *galactic cosmic rays*, is a long-standing problem which still has not found a definitive solution. Supernova remnants (SNRs) are widely believed to be the sites of galactic cosmic rays acceleration (e.g. see Drury (1991)). Nowadays, we do not yet have clear experimental evidence that the nuclear component of cosmic rays is accelerated there, even though theory predicts that they should be very efficiently accelerated (Berezhko and Völk, 2000; Ellison et al., 2000). If the SNRs are the actual sites of the cosmic-ray production, there will be interactions between the accelerated particles and the local interstellar matter. Originally, Drury et al. (1994) calculated the expected γ-ray fluxes from the SNRs assuming the model of diffusive shock acceleration and $\pi°$- production of the secondary γ-rays by charged cosmic-rays interacting with the local swept-up interstellar matter. An evident clue of the cosmic-ray acceleration in the SNRs would be the detection of high energy γ-rays from the SNRs which expand into or near dense matter regions, like giant molecular clouds, by current satellite and ground based detectors (Aharonian et al. (1994)). The EGRET instrument on board of the Compton Gamma-Ray Observatory has found GeV γ-ray signals associated with at least three of such SNRs: IC443 and γ-Cygni (Esposito et al. (1996)) and the Monoceros SNR/Rosette Nebula region (Jaffe et al. (1998), Romero et al.(1999)). It is believed that the observed γ-ray emission is the result of an interaction of the protons, accelerated by SNR shock waves, with the supernova matter itself or with the swept-up matter of the adjacent molecular clouds. Detection of these SNRs at TeV energies using ground-based imaging Cherenkov telescopes will offer almost direct evidence of the cosmic-ray acceleration at SNR shocks. Upper limits, after rather short exposures of about 10 hrs, for IC443, γ-Cygni and Monoceros SNR have been reported by the Whipple Collaboration (Buckley et al. (1998); Lessard et al. (1999)). The upper limit on the γ-ray flux above 1 TeV was derived out of the data taken with the HEGRA IACT array for relatively short time of 30 hrs for IC443 (Heß et al., (1997)).

2 The Monoceros Loop and its surroundings

The Monoceros Loop (SNR G205.5+0.5) was recognized as a SNR by Davies (1963) from 237 MHz radio observations. At optical wavelengths, the Monoceros Loop is an irregular bright ring of emission around 3.5° in diameter, centered on RA= $6^h 38^m 43^s$, DEC=$+6^\circ 30.2'$ (J2000) (see Fig. 1). The optical and radio properties of the Monoceros SNR/Rosette nebula have been studied in great detail by Davies et al. (1978) and Graham et al. (1982), respectively. The distance to the Monoceros Loop derived by Graham et al. (1982) using the formulae of Caswell and Lerche (1979) is of about 1.6 kpc, corresponding to a radial extension of 50-60 pc, which puts the remnant close to the Rosette nebula. The estimated age of the SNR is $3-15 \cdot 10^4$ yr, where the shock expands in the Sedov phase. According to Davies et al. (1978), the filamentary structures visible in the optical band for the southern part of the remnant are a proof of the possible interaction between the loop and the molecular cloud. Despite the fact that no detection of maser emission has been reported in the radio survey at 1720.5 MHz by Frail et al. (1996), an interaction between the two objects is not excluded.

The approximate nucleon density of the Rosette Nebula is $40\,\mathrm{cm}^{-3}$ as reported by Williams et al. (1995). However there is a large uncertainty in the nucleonic density which is averaged over the highly inhomogeneous cloud. Such a cloud might have clumps with enhanced density up to $n_H \leqslant 500\,\mathrm{cm}^{-3}$ as is the case for IC443 (Dickman et al. (1992)). As the Monoceros Loop is still in the Sedov phase, X-ray fluxes from this region can be expected. Leahy, Naranan and Singh (1985; 1986) mapped the Monoceros Loop using the EINSTEIN X-ray satellite and detected diffuse X-ray emission. The regions of diffuse X-ray emission are located on the rim of the remnant and they coincide with the densest region of optical filaments which show a high hardness ratio(> 0.3)[1]. Leahy et al. (1986) found that the Monoceros SNR emitted a 0.5-3 keV X-ray flux of $1.5 \times 10^{-10}\,\mathrm{erg\,cm^{-2}s^{-1}}$.

An observation carried out with the BeppoSAX satellite (Kaaret et al. (1999)) discovered a hard spectrum X-ray point source (SAX J0635+533) within the 95% probability circle of the EGRET detection, which was later identified as a binary pulsar. The unabsorbed flux from the source is $1.2 \times 10^{-11}\,\mathrm{ergscm^{-2}s^{-1}}$ in the 2-10 keV band. No extended emission has been reported from the BeppoSAX observations. However, the field of view of the BeppoSAX observations was relatively small as compared with the Einstein scan and the angular extension of the Monoceros SNR.

[1]Hardness ratio = (H-S)/(H+S) with H = 0.8 to 3.5 keV counts, S = 0.2 to 0.8 keV counts.

Table 1. Summary of the data taken towards the direction of the Monoceros/Rosette region with the HEGRA sistem of IACTs. T_{OBS} is the total observational time. T_{EFF} is the effective observational time after data cleaning. $\mathrm{R_{CR}}$ is the detection rate of the cosmic rays.

Obs. mode	T_{OBS} [hrs]	T_{EFF} [hrs]	$\mathrm{R_{CR}}$ [Hz]	Z.A.
ON	120	112	$\simeq$14	$20^\circ - 45^\circ$
OFF	20	20	$\simeq$14	$20^\circ - 30^\circ$

EGRET detected from the region associated with the Monoceros SNR/Rosette Nebula (see Fig. 1) an extended γ-ray emission (3EG-J0634+0521) in the energy range from 100 MeV up to 10 GeV at a 7σ confidence level (Jaffe et al. (1998)). This emission was interpreted as the γ-rays from the decay of π^0's produced by the interaction of the shock accelerated protons with ambient matter. The γ-ray flux in the range $\mathrm{E} \geqslant 100\,\mathrm{MeV}$ is $(5.36 \pm 0.43) \times 10^{-7}\,\mathrm{photons\,cm^{-2}s^{-1}}$. This source is listed in the 3d EGRET catalog with the name 3EG J0634+0521 (Hartman et al. (1999)).

3 HEGRA Data Analysis

The Monoceros SNR/Rosette Nebula region was observed at most in ON mode accompanied by approximately 20 hrs of OFF runs, taken at $+/-5^\circ$ away from the source in RA (see Table 1). For ON observations the BeppoSAX source SAX J0635+533 (RA $= 6^h 35^m 17.4^s$, DEC=$+5^\circ 33' 21''$ (J2000)) was adjusted to the center of the joint field of view (FoV) of the telescopes.

The stereoscopic reconstruction of air showers with the HEGRA system of IACTs allowed us to calculate the right ascension (RA) and declination (DEC) for each individual event as well as the angular slopes of the shower axis in the joint focal plane.

The two-dimensional map of the reconstructed events for a $2^\circ \times 2^\circ$ region of a FoV is shown in Fig. 2, after applying the standard cut on mean scaled Width $\langle \tilde{w} \rangle$ <1.1 to separate between hadrons and γ events (Konopelko et al. (1999)). We set the observational window to lay out on a quadrangular grid pattern with the cell size of $0.2^\circ \times 0.2^\circ$, which we have found suitable when searching for extended region: it is, in fact, comparable with the angular resolution of the HEGRA system of IACTs (RMS$\simeq 0.1^\circ$) and, at the same time, allows to have a relatively large number of pixels for computing the average number of CR hits per angular bin.

One can see from Fig. 2 that a few bins show an noticeable excess in a number of counts. Interestingly, four of these pixels are concentrated within the interaction region of the Monoceros SNR with the Rosette Nebula, as well as within the EGRET 95% probability circle. The analysis of about 40 hrs taken last year with the HEGRA IACTs (Lucarelli et al. (2001)) showed an excess in a number of reconstructed events with significance around 2.5 in five bins in the same

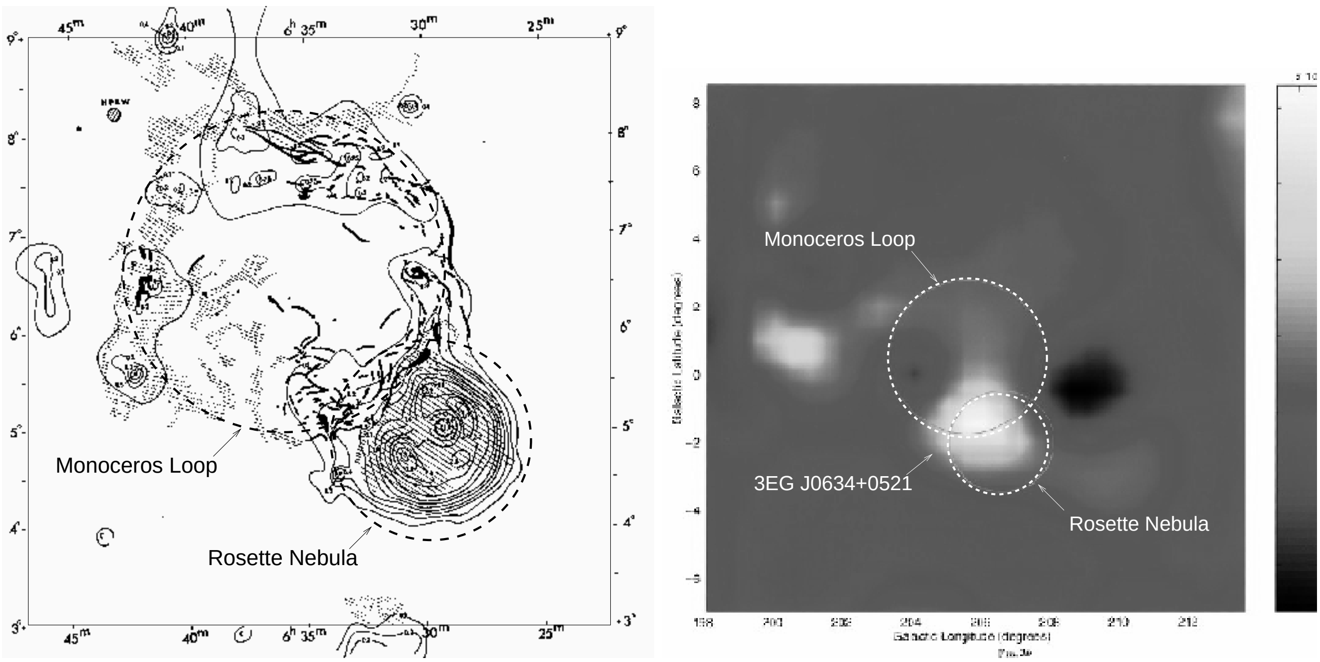

Fig. 1. Left panel: Radio and optical map of the Monoceros region taken from Davis et al. (1978). Contour levels show the radio observation at 2650 MHz. Thicker lines represent the optical bright filaments while shaded regions show the faint optical nebulosity. The Rosette nebula is visible in the south-east portion and dominates the radio map. Coordinates are referred to the 1950 epoch. Right panel: EGRET detection plot from Jaffe et al. (1998). Shown are the approximate extension and position of the Monoceros Loop (big circle) and of the Rosette nebula (small circle).

region of sky. We have compared this two-dimensional map with other regions close to the Monoceros SNR (e.g., the OFF regions and Geminga data) and we have not found any similar structure in any part of the camera.

3.1 Sensitivity area over the FoV

In observations of the Monoceros SNR/Rosette Nebula interacting region we were searching for possible point and extended γ-ray sources over the observational window of 1° radius around the center of the field of view. Although the entire field of view for the HEGRA system of IACTs is approximately of 2.2° radius, the region of almost equal sensitivity is limited by roughly 1°, as it was shown by our Monte Carlo simulations as well as with observations of the Crab Nebula by pointing the source 1-1.5° apart from the center of the camera field of view. Beyond 1° radius the calculated γ-ray event rate drastically falls off and the corresponding response function is given by

$$f(\theta) = [1+exp(a(\theta-\theta_0))]^{-1},\ a = 2.61deg^{-1}, \theta_0 = 2.03 \quad (1)$$

where θ is the angular distance from the center of field of view to the position of the source.

4 Confidence level of excess

Given the number of counts for each bin, we calculated the significance for each bin, S, using the approach suggested by Li & Ma (1983). Without any *a priori* information on the expected position of the source, the confidence level of an excess in each bin depends in addition on the total number of bins (number of trials) M, which may be considered as 80 independent measurements. In the present preliminary analysis, we considered for statistical analysis only those pixels which satisfy the condition $S > 3.5\sigma$ (σ is one standard deviation for the Gaussian distributed background events). The probability to achieve 3.5σ excess due to fluctuations in background for each individual pixel, p, can be simply calculated as

$$p = 1 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{3.5} e^{-\frac{1}{2}t^2} dt. \quad (2)$$

Finally the probability to get k pixels within our field of view is given by (see Li & Ma 81983))

$$p_k = C_M^k p^k (1-p)^{M-k} \quad (3)$$

(C_M^k is the binomial coefficient). The results of calculations for the different trigger multiplicities and M=80 using Eqn.(3) are provided in Table. 2.

In order to prove the formulae given by Eqn.(3) for our case, we made straightforward Monte Carlo simulations using the evaluated mean number of counts for ON data sample. The results are summarized in Table. 2. One can see rather good agreement with the direct Monte Carlo simulations (see Table.. 2 column p_k MC) taking into account a limited statistics in the Monte Carlo simulations which finally limits the accuracy of the calculations.

Table 2. Estimates of the confidence level for the excess events.

k	p_k Eqn.(3)	p_k MC
1	1.8310^{-2}	1.8310^{-2}
2	1.6810^{-4}	1.7010^{-4}
3	1.0210^{-6}	9.6010^{-7}
4	4.5510^{-9}	4.7010^{-9}

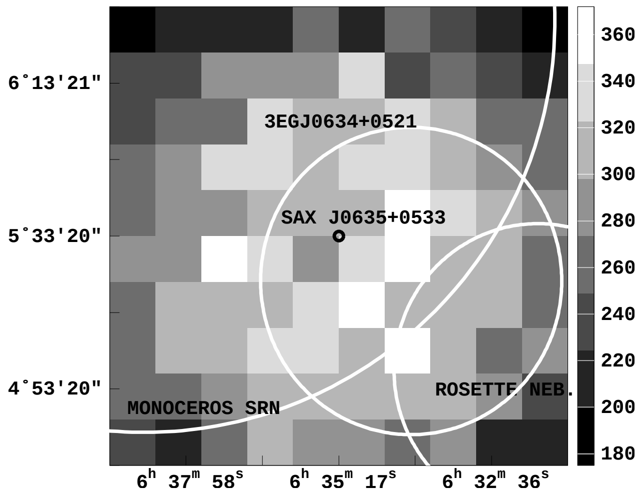

Fig. 2. Number of reconstructed events per $0.2^{\circ} \times 0.2^{\circ}$ bin over the FoV, after applying a cut on $\langle \tilde{w} \rangle$ <1.1. Superimposed are the approximate extends of the Monoceros Loop and Rosette nebula and the 95% error box of the EGRET source 3EG J0634+0521.

Finally, there were 80 cells within the established observational window. Applying curve 1 to take into account the non-uniform response of the camera at different distance from the center of FoV, we have calculated the average number of reconstructed events per pixel: $\langle N_{ON} \rangle \simeq 303\, counts/pixel$. The four pixels inside the EGRET source 95% error circle, show a number of entries between in the range from 364 to 369 counts, which correspond to 3.5-3.8 standard deviation from the average. Note that the calculations have shown that the 4-pixel coincidence within the observational window composed of 80 pixels is extremely rare case with the probability less than 10^{-8} and the corresponding estimate of confidence at 5.7σ.

5 Conclusion

The Monoceros SNR/Rosette Nebula interaction region was observed with the HEGRA stereoscopic system of 5 imaging air Čerenkov telescopes for about 140 hrs in 1999/2001. The preliminary analysis of the overall data reveals a few pixels of $0.2^{\circ} \times 0.2^{\circ}$ angular bins with a noticeable excess in a number of counts as compared with the predicted background contamination. All of those pixels are within 1° radius from the center of the FoV, which limits the region of constant sensitivity. These angular bins are closely associated with the Monoceros SNR/Rosette Nebula interaction region and the chance probability to have four pixel out of 80 with such excess due to the background fluctuations is very low. Further studies on the possible systematic effects which might be important in search for point like sources, and in particular extended sources, over the relatively broad field of view still have to be done. Different models of the background estimate need to be applied for the statistical verification of the observed event excess associated with the Monoceros SNR/Rosette Nebula interacting region. The final results of data reduction will be presented at the conference.

Acknowledgements. The support of the HEGRA experiment by the German Ministry for Research and Technology BMBF and by the Spanish Research Council CYCIT is acknowledged. We are grateful to the Instituto de Astrofisica de Canarias for the use of the site and for providing excellent working conditions.

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