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A search for TeV emission from SS-433 using the HEGRA CT-System

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Abstract. We present preliminary results of a search for TeV γ-ray emission from the Galactic microquasar/supernova remnant SS-433/W50. The HEGRA CT-System observed SS-433 for a total of ~55 hrs with various locations in the field of view considered as possible TeV sources. The jets of SS-433 make it potentially one of the most powerful accelerators of cosmic rays in our galaxy, and a particularly interesting site is a possible termination shock region $\sim 1.0^\circ$ east of SS-433, where cosmic ray acceleration may be taking place. The upper limit for TeV emission from this region constrains the shock-compressed magnetic field when interpreted in the synchrotron/inverse Compton framework.

1 Introduction

SS-433 is a Galactic microquasar (Mirabel and Rodríguez, 1999) powered by a compact object driving a parsec-scale jet and is likely associated with the supernova remnant W50. Strongly motivating observations at TeV γ-ray energies is the extraordinary kinetic *quiescent* power output of the jets in the range 10^{39} to 10^{41} erg s^{-1} (Margon, 1984; Kawai and Kotani, 1999; Safi-Harb and Ögelman, 1997). Such an output amounts to a significant fraction of that required to maintain the Galactic cosmic-ray (GCR) flux at Earth, few$\times 10^{41}$ erg s^{-1} (Blandford and Ostriker, 1980). SS-433/W50 may therefore be one of the most powerful, and indeed significant sites of GCR acceleration in our Galaxy. For SS-433, observations at TeV energies provide important constraints on the likelihood of this source contributing to GCR acceleration.

The framework described by Aharonian and Atoyan (1998) (hereafter, AA) suggests an appreciable flux of TeV γ-rays from SS-433 may be observed by present-day ground-based instruments. The idea is that inverse Compton scattering of cosmic microwave background (CMB) photons by electrons accelerated at the eastern jet termination shock $\sim 60'$ east of SS-433, labelled as 'e3' (Safi-Harb and Ögelman, 1997) or 'radio ear' (Dubner et al., 1998) will result in a TeV γ-ray flux. See figure 1 for definitions of various sites along the jet. e3 is likely an interaction region of the eastern jet particles and interstellar medium (ISM), and may contain a non-relativistic shock of the type suggested in SNR shells. A rather steep power law ($F_{\rm x} \propto E^{-\Gamma}$; $\Gamma = 3.7^{+2.3}_{-10.7}$) may be fitted to the e3 X-ray emission, although a thermal Bremsstrahlung interpretation for the X-ray emission is presently not ruled out due to the limiting resolution of ASCA & ROSAT (Safi-Harb and Ögelman, 1997). The spatial correlation however between the radio and X-ray emission (Brinkmann et al., 1996; Dubner et al., 1998) at e3 is strong evidence in favour of a non-thermal interpretation. Actually, a radio/X-ray correlation is noticed only for the e3 region, with other positions along the jet being essentially radio-quiet (Dubner et al., 1998). At other regions along the jet, mechanisms for the X-ray emission such as inverse Compton and/or synchrotron-self-Compton are invoked (Band and Grindlay, 1986). If the X-rays at e3 are indeed due to synchrotron emission, we can conclude that electrons there are accelerated to multi-TeV energies.

Observations at TeV energies can play a vital role in validating the synchrotron/inverse-Compton (S/IC) framework since the TeV γ-ray (f_γ) and X-ray ($f_{\rm x}$) energy fluxes are linked accordingly, for emission regions of same size in both X and γ-rays (Aharonian et al., 1997):

$$\frac{f_{\rm x}(0.1\,{\rm keV})}{f_\gamma(1\,{\rm TeV})} \sim 10\left(\frac{B}{10^{-5}\,{\rm G}}\right)^2 \qquad (1)$$

so that the shock-compressed B field can be determined explicitly, thus providing important information on particle acceleration properties. Correct energies for the above comparison arise from S/IC theory $\epsilon \sim 0.07(E/1\,{\rm TeV})(B/10^{-5}\,{\rm G})\,{\rm keV}$ so that at E ~1 TeV, a comparison of the X-ray energy flux at ϵ ~0.1 keV is required for reasonable values of $B \sim 10$ to 100 μG expected after shock compression.

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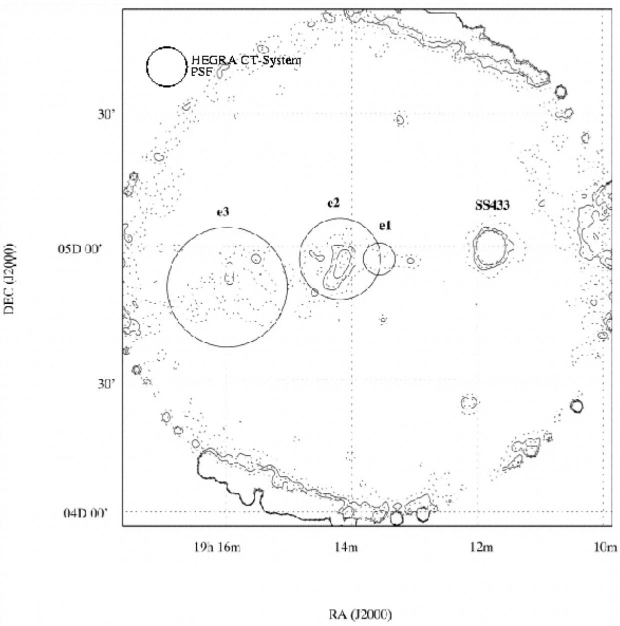

Fig. 1. ROSAT PSPC image (0.1 to 2.4 keV) of the eastern side of the SS-433/W50. Defined are a number of areas (e1, e2, e3) where separate spectral X-ray analyses were performed (Safi-Harb and Ögelman, 1997). Included is a circle depicting the PSF with radius, σ=0.1° (Aharonian et al., 2000b) for a point source of TeV γ-rays as imaged by the HEGRA CT-System.

Data	Obs. time (hrs)		Tracking	
Subset	ON	OFF	RA	Dec
1998	12.3	13.2	e2	e2
1999	6.7		e2	e2
1999 other	14.1	1.6	various	various
Gal. Plane	12.0		various	various
2000	10.4	3.3	e2	e2
Total	**55.5**	**18.1**		

Table 1. Summary of all SS-433 observations. The tracking position and observation time ON applies to the e2 region (J2000 RA $19.238^{\rm hr}$, Dec +4.917°). In the cases of various tracking, only those data with tracking distance within 1.5° of e2 are included. An extra software trigger was applied to all 1999 data to bring the CR trigger rate in line with 1998/2000 levels. A γ-ray energy threshold of 1 TeV applies, resulting from the average zenith angle of observations at $\sim 30°$.

2 Previous TeV Studies by HEGRA

SS-433 has been observed previously by the HEGRA CT-System (Konopelko et al., 1999) in dedicated campaigns in 1998/1999 for a total ∼19 hrs, and also during a 1999 scan of the Galactic plane for a total of ∼10 hrs. In these analyses, the regions e1, e2, e3 and SS-433 itself were *a-priori* considered as extended and/or point-like sources of interest (Aharonian et al., 2001; Rowell et al., 2000), with upper limits above 1 TeV at the 99% confidence level in the range 8 to 12% Crab flux being set. Interpreting the e3 upper limit (from the dedicated 1998/1999 observations) for a source region of radius 0.25° at 0.21×10^{-11} ph cm^{-2} s^{-1} (0.13 Crab units) in the S/IC framework described above results in a *lower limit* on the e3 magnetic field of $B \geq 13\ \mu$G. The lower limit arises since we used an upper limit to the 1 TeV flux. Our B field lower limit lies just below the range of equipartition values (20 to 60 μG) for e3 suggested by Safi-Harb and Ögelman (1997). Furthermore, the TeV flux upper limit lies close to the prediction by AA, when assuming reasonable values for the size of e3 (0.25° radius), electron injection power and spectral index.

3 Overall Observations and Results

Here, we report on the analysis of all SS-433 observations, the details of which are summarised in Table 1. Added to the previously reported analyses are extra data from 1999 labelled 'other' taken using the Wobble (Dec offset $\pm0.5°$) and ON/OFF tracking modes, and the most recent data taken in 2000, taken using ON/OFF tracking mode. For the Galactic plane case, a scan mode was used. Since OFF data were limited to $\sim 30\%$ of the ON total, the final analysis uses an alternative background method. The background was estimated from a subset of events rejected by the image shape criterion *mean-scaled-width* (MSW), providing a temporally and spatially consistent background to that of ON source data. This background model is particularly suited to datasets of various pointing positions and has been checked on the Crab (Rowell, 2000). The arrival direction of primary γ-rays and CRs are inferred by stereoscopic reconstruction of their extensive air shower (EAS) Čerenkov images, and a minimum of 2 out of 4 CT-System telescopes (CT3, 4, 5 & 6) is demanded for an event trigger. Further rejection of 'CR-like' images is based on the MSW parameter (Konopelko et al., 1999). Under the background model used here, we define $\rm MSW_\gamma$ ($0.4 < {\rm MSW} < 1.1$), representing a standard 'γ-ray like' selection, and $\rm MSW_{CR}$ ($1.4 \leq {\rm MSW} \leq 1.6$) as those images being 'CR-like'. For comparison $\rm MSW_{OFF}$ ($0.4 < {\rm MSW} < 1.1$) from dedicated OFF data may also be calculated. A slight systematic effect was noticed however in choosing $\rm MSW_{CR}$ as a background since these events are physically larger than those in $\rm MSW_\gamma$. Larger events will tend to trigger less efficiently than smaller events with distance θ from the tracking centre, giving rise to a fall-off in event density that may be characterised to first order by a simple linear function $f = p_1 + p_2\theta^2$ where f is an overestimation factor with respect to a flat response (as noticed for $\rm MSW_\gamma$). For each subset of data, f was used to correct the background estimate such that $\rm MSW_{CRcorr} = MSW_{CR}/\mathit{f}$, for each source of interest. Typical values for p_1 and p_2 are 1.1 and 0.1 respectively, implying that $\rm MSW_{CR}$ will systematically overestimate the background by about 10% at the tracking centre, but decreasing with distance to an underes-

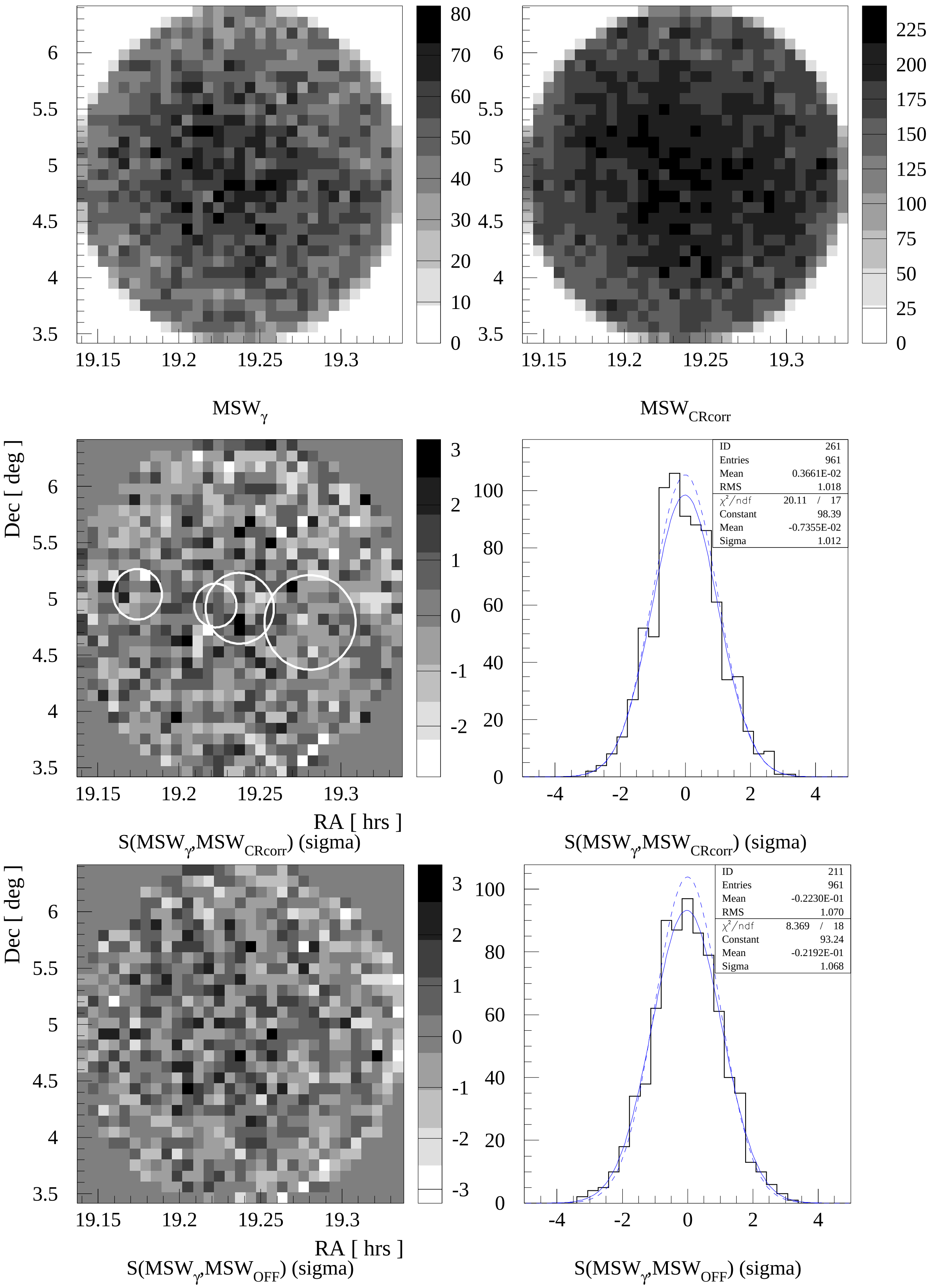

Fig. 2. Skymaps (2D plot of event directions at $0.1^\circ \times 0.1^\circ$ binning, 1.5° radius FOV) centred on the e2 position for MSW_γ (=ON source), $\mathrm{MSW}_{\mathrm{CRcorr}}$ (≡OFF source) and the statistical excess S. S is estimated using Eq. 9 of Li and Ma (1983) where the normalisation factor $\alpha = 0.282 = \Sigma_{\mathrm{FOV}}\mathrm{MSW}_{\mathrm{CR}}/\Sigma_{\mathrm{FOV}}\mathrm{MSW}_\gamma$ is estimated from the total events in the FOV. Very similar S distributions are obtained when using $\mathrm{MSW}_{\mathrm{CR}}$ (μ=0.020, σ=1.011). Overlayed on S are positions with optimal radii (θ_{op}) for each source under consideration (from left; ss-433, e1, e2 & e3). For comparision, included are S and it's distribution when using $\mathrm{MSW}_{\mathrm{OFF}}$ as a background.

Source	$\theta_{\rm op}$ (deg)	$\theta_{\rm s}$ (deg)	Obs. time (hrs)	MSW$_\gamma$	MSW$_{\rm CR}$	MSW$_{\rm CRcorr}$	S^a (σ)	$^b\phi^{99\%}_{\rm crab}$	$^c\phi^{99\%}_{\rm ph}$
e1	0.13	0.03	51.9	363	1248	1170	+1.6	**0.08**	**0.14**
e2	0.21	0.17	55.5	932	3329	3132	+1.4	**0.12**	**0.20**
e3	0.28	0.25	56.0	1557	5611	5344	+1.1	**0.14**	**0.24**
ss-433	0.15	0.08	49.9	456	1469	1408	+2.6	**0.11**	**0.20**

a. Statistical excess using eq. 9 of Li and Ma (1983) using MSW$_{\rm CRcorr}$ as background. Normalisation factor α = 0.282

b. $\phi^{99\%}_{crab}$ = 99% upper limit in units of Crab flux above 1 TeV, 1.75×10^{-11} ph cm^{-2}s^{-1} (Aharonian et al., 2000a)

c. $\phi^{99\%}_{ph}$ = 99% upper limit ($\times10^{-11}$ ph cm^{-2}s^{-1})

Table 2. Statistics of γ-ray (MSW$_\gamma$) and CR-like (MSW$_{\rm CR}$, MSW$_{\rm CRcorr}$) events for various sources in the field of SS-433/W50. See text for descriptions of source names.

timate at the edge. Skymaps of MSW$_\gamma$, MSW$_{\rm CRcorr}$ and the statistical excess of these quantities S for all SS-433 data are presented in figure 2, and were used to reveal any major systematic effects. The skymap binning is just smaller that the CT-System point spread function with $\sigma\sim0.1^\circ$. Events from each class of MSW were summed over an optimal radius pertaining to each source, $\theta^2_{\rm op}=\theta^2_{\rm pt}+\theta^2_{\rm s}$ where $\theta_{\rm pt}\sim0.126^\circ$ is the optimal cut for a point source under background-dominated statistics, and $\theta_{\rm s}$ is the actual source radius. Thus we assume that the source region is of a Gaussian morphology. Table2 presents the overall results for each source of interest where the excess significance is estimated using MSW$_{\rm CRcorr}$ as a background. For none of the chosen sources a statistically significant excess was found. Subsequent upper limits ($\phi^{99\%}$) were estimated using $\sim$26 hrs data from the Crab (at zenith angles $\sim30^\circ$) as a basis, also taking into consideration the exposure $t_{\rm src}$ and average γ-ray trigger efficiency of each source $\bar{\eta}_{\rm src}$ [1] with respect to those of the Crab $t_{\rm crab}$, $\bar{\eta}_{\rm crab}$:

$$\phi^{99\%}_{\rm crab}=\frac{N^+_{\rm src}}{N^-_{\rm crab}}\frac{t_{\rm crab}}{t_{\rm src}}\frac{\bar{\eta}_{\rm crab}}{\bar{\eta}_{\rm src}} \quad (2)$$

Here, using the method of Helene (1983), $N^+_{\rm src}$ is the 99% upward fluctuated source excess (ie. MSW$_\gamma-$MSW$_{\rm CRcorr}$), and $N^-_{\rm crab}$ is the 99% downward fluctuated Crab excess.

4 Discussion/Conclusion

Analysis to-date of over 50 hrs data on the SS-433/W50 region has revealed no evidence for TeV emission and 99% upper limits above 1 TeV in the range 8 to 14% Crab flux were set. Taking the upper limit from the e3 region, we may estimate a lower limit on the shock-compressed field within the S/IC framework as $B>13\ \mu$G, This represents no improvement upon the previously published limits (Rowell et al., 2000; Aharonian et al., 2001), and can be attributed to an excess significance from this analysis which is higher than that obtained under previous analyses. Results here should be considered preliminary however as further analysis will investigate methods considered more sensitive, such as that in use by Lampeitl (2001); Aharonian et al. (2001) in which $>$2 telescope triggers are demanded for event acceptance.

[1] $\eta(\theta)=1.0/(1.0+\exp(2.607(\theta-2.034)))$ (Konopelko, 2001)

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