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Letter to the Editor

Discovery of a point-like very-high-energy γ-ray source in Monoceros

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ABSTRACT

Aims. The complex Monoceros Loop SNR/Rosette Nebula region contains several potential sources of very-high-energy (VHE) γ-ray emission and two as yet unidentified high-energy EGRET sources. Sensitive VHE observations are required to probe acceleration processes in this region.
Methods. The HESS telescope array has been used to search for very high-energy γ-ray sources in this region. CO data from the NANTEN telescope were used to map the molecular clouds in the region, which could act as target material for γ-ray production via hadronic interactions.
Results. We announce the discovery of a new γ-ray source, HESS J0632+057, located close to the rim of the Monoceros SNR. This source is unresolved by HESS and has no clear counterpart at other wavelengths but is possibly associated with the weak X-ray source 1RXS J063258.3+054857, the Be-star MWC 148 and/or the lower energy γ-ray source 3EG J0634+0521. No evidence for an associated molecular cloud was found in the CO data.

Key words. gamma rays: observations

1. Introduction

Shell-type supernova remnants (SNRs) have been identified as particle accelerators via their very-high-energy (VHE; E > 100 GeV) γ-ray and non-thermal X-ray emission (see e.g. Aharonian et al. 2006a and Koyama et al. 1997). It has been suggested that interactions of particles accelerated in SNR with nearby molecular clouds should produce detectable γ-ray emission (Aharonian et al. 1994). For this reason the well-known Monoceros Loop SNR (G 205.5+0.5, distance ~1.6 kpc Graham et al. 1982; Leahy et al. 1986), with its apparent interaction with the Rosette Nebula (a young stellar cluster/molecular cloud complex, distance 1.4 ± 0.1 kpc Hensberge et al. 2000) is a prime target for observations with VHE γ-ray instruments.

For the case of *hadronic* cosmic rays (CRs) interacting in the interstellar medium to produce pions and hence γ-rays via π^0 decay, a spatial correlation between γ-ray emission and tracers of interstellar gas is expected. Such a correlation was used to infer the presence of a population of recently accelerated CR hadrons in the Galactic Centre region (Aharonian et al. 2006b). This discovery highlights the importance of accurate mapping of available target material for the interpretation of TeV γ-ray emission.

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The NANTEN 4 m diameter sub-mm telescope at Las Campanas observatory, Chile, has been conducting a ^{12}CO ($J = 1 \rightarrow 0$) survey of the Galactic plane since 1996 (Mizuno & Fukui 2004). The Monoceros region is covered by this survey and the NANTEN data are used here to trace the target material for interactions of accelerated hadrons.

2. HESS observations and results

The observations described here took place between March 2004 and March 2006 and comprise 13.5 h of data after data quality selection and dead-time correction. The data were taken over a wide range of zenith angles from 29 to 59 degrees, leading to a mean energy threshold of 400 GeV with so-called *standard cuts* used here for spectral analysis and 750 GeV with the *hard cuts* used here for the source search and position fitting. These cuts are described in detail in Aharonian et al. (2006c).

A search in this region for point-like emission was made using a 0.11° *On source* region and a ring of mean radius 0.5° for *Off source* background estimation (see Berge et al. 2006 for details). Figure 1 shows the resulting significance map, together with CO data from NANTEN, radio contours and the positions of all Be-stars in this region. The peak significance in the field is 7.1σ. The number of statistical trials associated with a search of the entire field of view, in 0.01° steps along both axes, is $\approx 10^5$. The measured peak significance corresponds to 5.3σ after accounting for these trials. A completely independent analysis based on a fit of camera images to a shower model (*Model Analysis* described in de Naurois 2006), yields a significance of 7.3σ (5.6σ post-trials).

The best fit position of the new source is $6^{\rm h}32^{\rm m}58.3^{\rm s}$, $+5°48'20''$ (RA/Dec J2000) with $28''$ statistical errors on each axis, and is hence identified as HESS J0632+057. Systematic errors are estimated at $20''$ on each axis. There is no evidence for intrinsic extension of the source and we derive a limit on the rms size of the emission region of $2'$ (at 95% confidence), under the assumption that the source follows a Gaussian profile. This source size upper limit is shown as a dashed circle in the bottom panel of Fig. 1. Figure 2 demonstrates the point-like nature of the source. The angular distribution of excess γ-ray-like events with respect to the best fit position is shown together with the expected distribution for a point-like source.

The reconstructed energy spectrum of the source is consistent with a power-law: $dN/dE = k(E/1 \text{ TeV})^{-\Gamma}$ with photon index $\Gamma = 2.53 \pm 0.26_{\rm stat} \pm 0.20_{\rm sys}$ and a flux normalisation $k = 9.1 \pm 1.7_{\rm stat} \pm 3.0_{\rm sys} \times 10^{-13}$ cm^{-2} s^{-1} TeV^{-1}. Figure 3 shows the HESS spectrum together with that for the unidentified EGRET source 3EG J0634+0521 (discussed below) and an upper limit derived for TeV emission from 3EG J0634+0521 using the HEGRA telescope array (Aharonian et al. 2004), converted from an integral to a differential flux using the spectral shape measured by HESS. We find no evidence for flux variability of HESS J0632+057 within our dataset. However, we note that due to the weakness of the source and sparse sampling of the light-curve, intrinsic variability of the source is not strongly constrained. The bulk of the available data was taken in two short periods in December 2004 (P1, 4.7 h) and November/December 2005 (P2, 6.2 h). The integral fluxes (above 1 TeV) in these two periods were: $6.3 \pm 1.8 \times 10^{-13}$ cm^{-2} s^{-1} (P1) and $6.4 \pm 1.5 \times 10^{-13}$ cm^{-2} s^{-1} (P2).

Amongst the candidate VHE sources in this field is the 34 ms binary pulsar SAX J0635.2+0533. There is no significant γ-ray emission at the position of this object and we derive a 99% confidence upper limit on the integral flux, $F(>1 \text{ TeV})$, of 2.6×10^{-13} cm^{-2} s^{-1}, assuming an E^{-2} type spectrum.

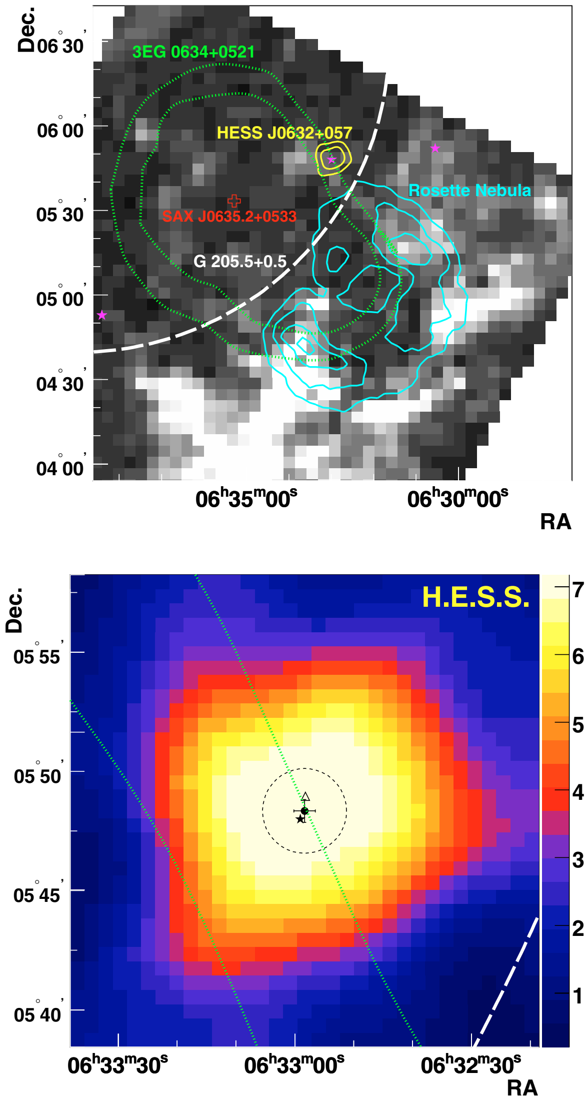

Fig. 1. *Top*: the Monoceros SNR / Rosette Nebula region. The greyscale shows velocity integrated (0–30 km s^{-1}) ^{12}CO ($J = 1 \rightarrow 0$) emission from the NANTEN Galactic Plane Survey (white areas have highest flux). Yellow contours show 4 and 6σ levels for the statistical significance of a point-like γ-ray excess. Radio observations at 8.35 GHz from Langston et al. (2000) are overlaid as cyan contours, and illustrate the extent of the Rosette Nebula. The nominal Green (2004) Catalogue position/size of the Monoceros SNR is shown as an (incomplete) dashed circle. The 95% and 99% confidence regions for the position of the EGRET source 3EG 0634+0521 are shown as a dotted green contours. The binary pulsar SAX J0635.2+0533 is marked with a square and Be-stars with pink stars. *Bottom*: an expanded view of the centre of the top panel showing HESS significance as a colour scale. The rms size limit derived for the TeV emission is shown as a dashed circle. The unidentified X-ray source 1RXS J063258.3+054857 is marked with a triangle and the Be-star MCW 148 with a star.

3. Possible associations of HESS J0632+057

The new VHE source HESS J0632+057 lies in a complex region and several associations with objects known at other wavelengths seem plausible. We therefore consider each of these potential counterparts in turn.

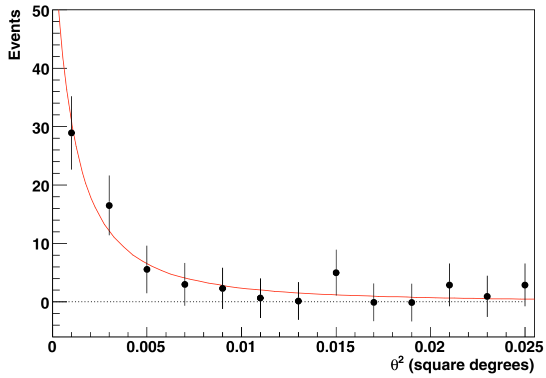

Fig. 2. Distribution of excess (candidate γ-ray) events as a function of squared angular distance from the best fit position of HESS J0632+057 (points), compared to the expectation for this dataset from Monte-Carlo simulations (smooth curve).

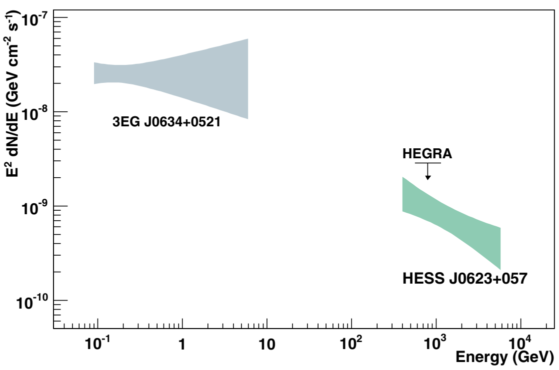

Fig. 3. Reconstructed VHE γ-ray spectrum of HESS J0632+057 compared to the HE γ-ray source 3EG J0634+0521. An upper limit derived for 3EG J0634+0521 at TeV energies using the HEGRA instrument is also shown.

The Monoceros Loop SNR is rather old in comparison to the known VHE γ-ray shell-type SNRs RX J1713.7−3946 (Aharonian et al. 2006a), RX J0852.0−4622 (Aharonian et al. 2005b) and Cas-A (Aharonian et al. 2001). All these objects have estimated ages less than ~2000 years, in contrast the Monoceros Loop SNR has an age of $\sim 3 \times 10^4$ years (Leahy et al. 1986). This supernova remnant therefore appears to be in a different evolutionary phase (late Sedov or Radiative) compared to these known VHE sources. However, CR acceleration may occur even at this later evolutionary stage (see for example Yamazaki et al. 2006). The principal challenge for a scenario involving the Monoceros Loop is to explain the very localised VHE emission at only one point on the SNR limb. The interaction of the SNR with a compact molecular cloud is one possible solution. In this scenario (and indeed any π^0 decay scenario) for the observed γ-ray emission, a correlation is expected between the TeV emission and the distribution of target material. An unresolved molecular cloud listed in a CO survey at 115 GHz (Oliver et al. 1996) lies rather close to HESS J0623+057, at $l = 205.75$ $b = -1.31$. The distance estimate for this cloud (1.6 kpc) is consistent with that for the Monoceros SNR, making it a potential target for hadrons accelerated in the SNR. However, as can be seen clearly in the NANTEN data in Fig. 1, the intensity peak of this cloud is significantly shifted to the East of the HESS source. We find no evidence in the NANTEN data for any clouds along the line of sight to the HESS source.

3EG J0634+0521 is an unidentified EGRET source (Hartman et al. 1999) with positional uncertainties such that HESS J0632+057 lies close to the 99% confidence contour. Given that this source is flagged as possibly extended or confused, a positional coincidence of these two objects seems plausible. Furthermore, the reported third EGRET catalogue flux above 100 MeV ($(25.5 \pm 5.1) \times 10^{-8}$ photons cm^{-2} s^{-1} with a photon index of 2.03 ± 0.26, see Fig. 3), is consistent with an extrapolation of the HESS spectrum. A global fit of the two spectra gives a photon index of 2.41 ± 0.06.

1RXS J063258.3+054857 is a faint ROSAT source (Voges et al. 2000) which lies 36″ from the HESS source with a positional uncertainty of 21″ (see Fig. 1 bottom). Given the uncertainties on the positions of both objects this X-ray source can certainly be considered a potential counterpart of HESS J0632+057. The chance probability of the coincidence of a ROSAT Faint Source Catalogue source within the HESS error circle is estimated as 0.1% by scaling the total number of sources in the field of view. The ROSAT source is rather weak, with only 4 counts detected above 0.9 keV, spectral comparison is therefore rather difficult. In the scenario where the γ-ray emission is interpreted as inverse Compton emission from a population of energetic electrons, the ROSAT source could be naturally ascribed to the synchrotron emission of the same electron population. However, the low level of the X-ray emission ($\sim 10^{-13}$ erg cm^{-2} s^{-1}) in comparison with the TeV flux ($\sim 10^{-12}$ erg cm^{-2} s^{-1}) implies a very low magnetic field ($\ll 3\,\mu$G) unless a strong radiation source exists in the neighbourhood of the emission region and/or the X-ray emission suffers from substantial absorption. Observations at >4 keV are required to resolve this absorption issue. In a π^0 decay scenario for the γ-ray source, secondary electron production via muon decay is expected along with γ-ray emission. The synchrotron emission of these secondary electrons would in general produce a weaker X-ray source than the IC scenario, probably compatible with the measured ROSAT flux.

MWC 148 (HD 259440) is a massive emission-line star of spectral type B0pe which lies within the HESS error circle. The chance probability of this coincidence is hard to assess, as there was no a-priori selection of stellar objects as potential γ-ray sources. However, given the presence of only 3 Be-type stars in the field of view of the HESS observation (see Fig. 1) and the solid angle of the HESS error circle, the naive chance probability of the association is 10^{-4}. Stars of this spectral type have winds with typical velocities and mass loss rates of 1000 km s^{-1} and 10^{-7} $M_\odot$/year, respectively. Plausible acceleration sites are in strong internal or external shocks of the stellar wind. We estimate that an efficiency of 1–10% in the conversion of the kinetic energy of the wind into γ-ray emission would be required to explain the HESS flux (assuming this star lies at the distance of the Rosette Nebula). However, as no associations of similar stars with point-like γ-ray sources were found in the HESS survey of the inner Galaxy, this scenario seems rather unlikely.

A related possibility is that MWC 148 is part of a binary system with an, as yet undetected, compact companion. Such a system might then resemble the known VHE γ-ray source PSR B1259-63/SS 2883 (Aharonian et al. 2005a). Further multi-wavelength observations are required to confirm or refute this scenario.

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