Discovery of a point-like very-high-energy $\gamma$-ray source in Monoceros

F. A. Aharonian$^{1,13}$, A. G. Akhperjanian$^2$, A. R. Bazer-Bachi$^3$, B. Behera$^{14}$, M. Beilicke$^4$, W. Benbow$^1$, D. Berge$^{1,*}$, K. Bernlohr$^{1,5}$, C. Boisson$^6$, O. Bolz$^1$, V. Borrel$^1$, I. Braun$^1$, E. Brion$^7$, A. M. Brown$^8$, R. Bühler$^1$, I. Büsching$^9$, T. Boutelier$^{17}$, S. Carrigan$^1$, P. M. Chadwick$^8$, L.-M. Choulet$^{10}$, G. Coignet$^{11}$, R. Cornils$^4$, L. Costamante$^{1,23}$, B. Degrange$^{10}$, H. J. Dickinson$^8$, A. Djannati-Atai$^{12}$, W. Domainko$^1$, L. O. Drury$^{13}$, G. Dubus$^{10}$, K. Egberts$^1$, D. Emmanoulopoulos$^{14}$, P. Espigat$^{12}$, C. Farnier$^{15}$, F. Feinstein$^{15}$, A. Förster$^1$, G. Fontaine$^{10}$, Seb. Funk$^5$, S. Funk$^1$, M. Fußling$^5$, Y. A. Gallant$^{15}$, B. Giebels$^{10}$, J. F. Glicenstein$^7$, B. Glück$^{16}$, P. Goret$^7$, C. Hadjichristidis$^8$, D. Hauser$^1$, M. Hauser$^{14}$, G. Heinzelmann$^4$, G. Henri$^{17}$, G. Hermann$^1$, J. A. Hinton$^{1,14,**}$, A. Hoffmann$^{18}$, W. Hofmann$^1$, M. Holleran$^9$, S. Hoppe$^1$, D. Horns$^{18}$, A. Jacholkowska$^{15}$, O. C. de Jager$^9$, K. Kendziorra$^{19}$, M. Kerschhaggl$^5$, B. Khelifi$^{10}$, Nu. Komin$^{15}$, K. Kosack$^1$, G. Lamanna$^{11}$, I. J. Latham$^8$, R. Le Gallou$^4$, A. Lemière$^{12}$, M. Lemoine-Goumard$^{10}$, T. Lohse$^3$, J. M. Martin$^6$, O. Martineau-Huynh$^{19}$, A. Marcowith$^{3,15}$, C. Masterson$^{1,23}$, G. Maurin$^{12}$, T. J. L. McComb$^8$, E. Moulin$^{15,3}$, M. de Naurois$^{19}$, D. Nedbal$^{20}$, S. J. Nolan$^8$, A. Noutsos$^8$, J.-P. Olive$^3$, K. J. Orford$^8$, J. L. Osborne$^8$, M. Panter$^1$, G. Pedretti$^{17}$, P.-O. Petrucci$^{17}$, S. Pita$^{12}$, G. Pühlhofer$^{14}$, M. Punch$^{12}$, S. Ranchon$^{11}$, B. C. Raubenheimer$^5$, M. Raue$^4$, S. M. Rayner$^8$, O. Reimer$^{***}$, J. Ripken$^4$, L. Rob$^{20}$, L. Rolland$^7$, S. Rosier-Lees$^{11}$, G. Rowell$^{1,7}$, J. Ruppel$^{21}$, V. Sahakian$^2$, A. Santangelo$^{18}$, L. Sauge$^{17}$, S. Schlenker$^5$, R. Schlickeiser$^{21}$, R. Schröder$^{21}$, U. Schwanke$^5$, S. Schwarzburg$^{18}$, S. Schwemmer$^{14}$, A. Shalchi$^{21}$, H. Sol$^{6}$, D. Spangler$^8$, R. Steenkamp$^{22}$, C. Stegmann$^{16}$, G. Superina$^{10}$, P. H. Tam$^{14}$, J.-P. Tavernet$^{19}$, R. Terrier$^{12}$, M. Tluczykont$^{10,23}$, C. van Eldik$^1$, G. Vasileiadis$^{15}$, C. Venter$^9$, J. P. Vialle$^{11}$, P. Vincent$^{19}$, H. J. Völk$^1$, S. J. Wagner$^{14}$, M. Ward$^8$, Y. Moriguchi$^{24}$, and Y. Fukui$^{24,25}$

(Affiliations can be found after the references)

Received 14 February 2007 / Accepted 27 March 2007

ABSTRACT

Aims. The complex Monoceros Loop SNR/Rosette Nebula region contains several potential sources of very-high-energy (VHE) $\gamma$-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 $\gamma$-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 $\gamma$-ray production via hadronic interactions.

Results. We announce the discovery of a new $\gamma$-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 $\gamma$-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) $\gamma$-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 $\gamma$-ray emis-sion (Aharonian et al. 1994). For this reason the well-known Monoceros Loop SNR (G 205.5+0.5, distance $\sim 1.6$ 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 $1.4 \pm 0.1$ kpc Hensberge et al. 2000) is a prime target for observations with VHE $\gamma$-ray instruments.

For the case of hadronic cosmic rays (CRs) interacting in the interstellar medium to produce pions and hence $\gamma$-rays via $\pi^0$ decay, a spatial correlation between $\gamma$-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 $\gamma$-ray emission.
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 ≈10⁷. 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 6h32m58.3s, +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: \( \frac{dN}{dE} = k(E/1 \text{ TeV})^{-\Gamma} \) with photon index \( \Gamma = 2.53 \pm 0.26_{\text{stat}} \pm 0.20_{\text{sys}} \) and a flux normalisation \( k = 9.1 \pm 1.7_{\text{stat}} \pm 3.0_{\text{sys}} \times 10^{-13} \text{ cm}^{-2} \text{s}^{-1} \text{ TeV}^{-1} \). 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 \( \pm 1.8 \times 10^{-13} \text{ cm}^{-2} \text{s}^{-1} \) (P1) and 6.4 \( \pm 1.5 \times 10^{-13} \text{ cm}^{-2} \text{s}^{-1} \) (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 \( \times 10^{-13} \text{ cm}^{-2} \text{s}^{-1} \), assuming an \( E^{-2} \) type spectrum.

### 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.
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 ~3 × 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 n°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 ± 5.1) × 10^{-3} 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 (~10^{-15} erg cm^{-2} s^{-1}) in comparison with the TeV flux (~10^{-12} erg cm^{-2} s^{-1}) implies a very low magnetic field (~3 μG) 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 n°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 in general would 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⊙/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.

Acknowledgements. The support of the Namibian authorities and of the University of Namibia in facilitating the construction and operation of HESS is gratefully acknowledged, as is the support by the German Ministry for Education and Research (BMBF), the Max Planck Society, the French Ministry for Research, the CNRS-IN2P3 and the Astroparticle Interdisciplinary Programme.
of the CNRS, the UK Particle Physics and Astronomy Research Council (PPARC), the IPNP of the Charles University, the South African Department of Science and Technology and National Research Foundation, and by the University of Namibia. We appreciate the excellent work of the technical support staff in Berlin, Durham, Hamburg, Heidelberg, Palaiseau, Paris, Saclay, and in Namibia in the construction and operation of the equipment. The NANTEN project is financially supported from JSPS (Japan Society for the Promotion of Science) Core-to-Core Program, MEXT Grant-in-Aid for Scientific Research on Priority Areas, and SORST-JST (Solution Oriented Research for Science and Technology: Japan Science and Technology Agency). We would also like to thank Stan Owocki and James Unquhart for very useful discussions.

References
Aharonian, F. A., Drury, L. O., & Voelk, H. J. 1994, A&A, 285, 645
Aharonian, F., Akhperjanian, A., Barrio, J., et al. 2001, A&A, 370, 112
Aharonian, F. A., Akhperjanian, A. G., Beilicke, M., et al. 2004, A&A, 417, 973
Aharonian, F., Akhperjanian, A. G., Aye, K.-M., et al. 2005a, A&A, 442, 1
Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2005b, A&A, 437, L7
Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006a, A&A, 449, 223
Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006b, Nature, 439, 695
Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006c, A&A, 457, 899

Berger, D., Funk, S., & Hinton, J. 2006 [arXiv:astro-ph/0612674]
de Naurois, M. 2006 [arXiv:astro-ph/0612747]
Graham, D. A., Haslam, C. G. T., Salter, C. J., & Wilson, W. E. 1982, A&A, 109, 145
Green, D. A. 2004, Bull. Astron. Soc. India, 32, 335
Hartman, R. C., Bertsch, D. L., Bloom, S. D., et al. 1999, ApJS, 123, 79
Hensberge, H., Pavlovski, K., & Verschueren, W. 2000, A&A, 358, 553
Koyama, K., Kitagasa, K., Matsuzaaki, K., et al. 1997, PASJ, 49, L7
Langston, G., Minter, A., D’Addario, L., et al. 2000, AJ, 119, 2801
Leathy, D. A., Naranan, S., & Singh, K. P. 1986, MNJAS, 220, 501
Mizuno, A., & Fukui, Y. 2004, in Milky Way Surveys: The Structure and Evolution of our Galaxy, ed. D. Clemens, R. Shah, & T. Brainerd, ASP Conf. Ser., 317, 59
Oliver, R. J., Masheder, M. R. W., & Thaddeus, P. 1996, A&A, 315, 578
Voges, W., Aschenbach, B., Boller, T., et al. 2000, IAU Circ., 7432, 1
Yamazaki, R., Kohri, K., Bamba, A., et al. 2006, MNRAS, 371, 1975

1 Max-Planck-Institut für Kernphysik, PO Box 103980, 69029 Heidelberg, Germany
2 Yerevan Physics Institute, 2 Alikhanian Brothers St., 375036 Yerevan, Armenia
3 Centre d’Etude Spatiale des Rayonnements, CNRS/UPS, 9 Av. du Colonel Roche, BP 4346, 31029 Toulouse Cedex 4, France
4 Universitét Hamburg, Institut für Experimentalphysik, Luruper Chaussee 149, 22761 Hamburg, Germany
5 Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, 12489 Berlin, Germany
6 LUTH, UMR 8102 du CNRS, Observatoire de Paris, Section de Meudon, 92195 Meudon Cedex, France
7 DAPNIA/DSM/CEA, CE Saclay, 91191 Gif-sur-Yvette Cedex, France
8 University of Durham, Department of Physics, South Road, Durham DH1 3LE, UK
9 Unit for Space Physics, West-North University, Potchefstroom 2520, South Africa
10 Laboratoire Leprince-Ringuet, IN2P3/CNRS, Ecole Polytechnique, 91128 Palaiseau, France
11 Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3/CNRS, 9 Chemin de Bellevue – BP 110, 74941 Annecy-le-Vieux Cedex, France
12 APC, 11 Place Marcelin Berthelot, 75231 Paris Cedex 05, France
13 Dublin Institute for Advanced Studies, 5 Merrion Square, Dublin 2, Ireland
14 Landessternwarte, Universität Heidelberg, Königstuhl, 69117 Heidelberg, Germany
15 Laboratoire de Physique Théorique et Astroparticules, IN2P3/CNRS, Université Montpellier II, CC 70, Place Eugène Bataillon, 34095 Montpellier Cedex 5, France
16 Laboratoire d’Astrophysique de Grenoble, INSU/CNRS, Université Joseph Fourier, BP 53, 38041 Grenoble Cedex 9, France
17 Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, 72076 Tübingen, Germany
18 Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Universités Paris VI & VII, 4 Place Jussieu, 75252 Paris Cedex 5, France
19 Institute of Particle and Nuclear Physics, Charles University, V Holesovickev 2, 180 00 Prague 8, Czech Republic
20 Instituto de Theoretische Physik, Lehrstuhl IV: Weltraum und Astrophysik, Ruhr-Universität Bochum, 44780 Bochum, Germany
21 Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Universités Paris VI & VII, 4 Place Jussieu, 75252 Paris Cedex 5, France
22 University of Namibia, Private Bag 13301, Windhoek, Namibia
23 European Associated Laboratory for Gamma-Ray Astronomy, jointly supported by CNRS and MPG
24 Department of Astrophysics, Nagoya University, Chikusa-ku, Nagoya 464-8602, Japan
25 Nagoya University Southern Observatories, Nagoya 464-8602, Japan