29th International Cosmic Ray Conference Pune (2005) **4**, 127–130

VHE observations of pulsar wind nebulae with H.E.S.S.

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The H.E.S.S. detector is an array of atmospheric-Cherenkov telescopes dedicated to the observation of very high energy (VHE) γ-rays. Situated in Namibia, the full four-telescope array is operational since December 2003. Among many types of targets, the H.E.S.S. collaboration is studying pulsar wind nebulae (PWN) in the VHE γ-ray domain. These objects can produce VHE emission by the inverse Compton process, whereby relativistic electrons and positrons in the shocked pulsar wind interact with lower-energy ambient photons. The PWN inside MSH 15-52, G 0.9+0.1 and near the Vela pulsar have been observed by H.E.S.S. since 2004. The results of these observations are reported here.

1. Introduction

Some young neutron stars are surrounded by a synchrotron nebula detected in radio and X-rays. The Crab nebula is an example of one such pulsar wind nebula (PWN). The central source, with a typical surface magnetic field of 10^{12} G and an initial rotational period between 10 and 100 ms, powers the surrounding nebula. The total energy available is can range up to 10^{49} erg, and is a potential power source for production of very high energy (VHE, >100 GeV) γ-rays. The rotational energy of the pulsar is believed to be mostly carried away by a relativistic wind of electrons and positrons (probably with an additional hadronic component). The interaction of this wind with the surrounding medium creates a relativistic shock wave, where the charged particles are thought to be accelerated to high energies by the Fermi mechanism (e.g. [1]). The particle acceleration could be alternatively linked to driven reconnection of the alternating magnetic field at the pulsar wind termination shock [14]. The interaction of accelerated leptons with ambient photon fields (e.g. the CMBR or local IR photons) can produce VHE γ-rays via the Inverse Compton (IC) process. Alternatively, p-p collisions may also produce VHE photons (e.g. [7]).

We present here the results of VHE γ-ray observations in 2004 and 2005 of the composite supernova remnant (SNR) MSH 15-52, G 0.9+0.1 and the central region of the Vela SNR by the High Energy Stereoscopic System (H.E.S.S.) experiment. H.E.S.S. is an atmospheric-Cherenkov detector dedicated to the observation of γ-rays above 100 GeV up to tens of TeV. Situated in Namibia at 1800 metres above sea level, the full four-telescope array is operational since December 2003. A complete description of this detector and of its performance can be found in [12]. The standard techniques of event reconstruction, background estimation and spectral extraction used for the presented results are described in [2].

2. Observations of MSH 15-52

MSH 15-52 is a composite SNR, containing a 150-ms pulsar (PSR B1509-58) that powers a PWN, a surrounding SNR shell (G 320.4-1.2) and an H_α nebula (RCW 89), as seen in radio and X-rays ([4] and references within). The distance to the object and the pulsar spindown age are estimated to 5.2±1.4 kpc and 1700 years, respectively. The PWN, as seen in X-rays, appears to be elongated and roughly centered on the pulsar with two arms extending along the NW and SE directions. This morphology has been observed in X-rays up to 10 keV.

This region has been observed with H.E.S.S. between March and June 2004, yielding 22.1 hours (live time)

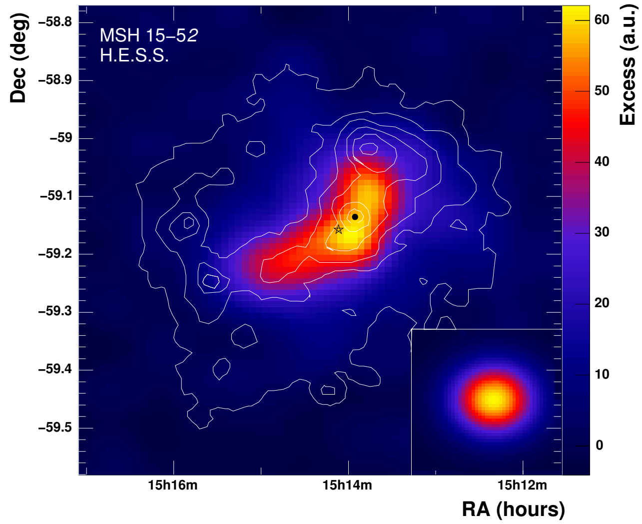
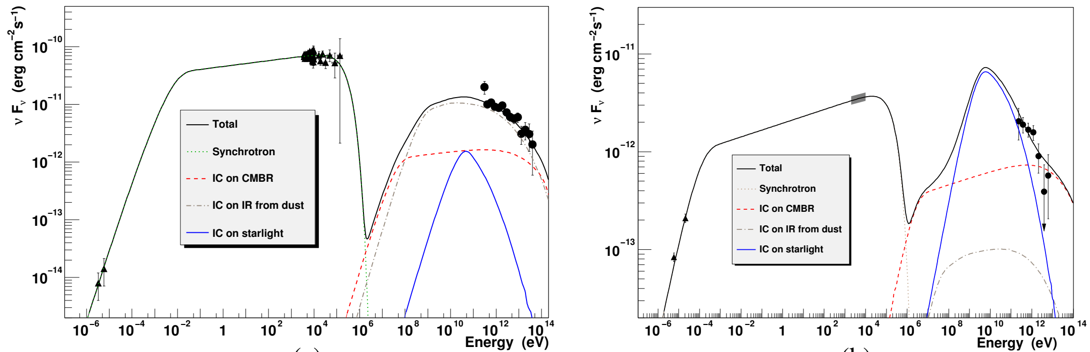


Figure 1. Smoothed excess maps of MSH 15-52 above ∼900 GeV. The right-bottom inset shows the simulated PSF smoothed identically. The white contour lines are the X-ray count rate levels as seen by ROSAT (0.1–2.4 keV). The black star and circle are the excess Gaussian centroid and the pulsar position, respectively.

of good quality data with an average energy threshold of ∼280 GeV. An excess with a significance of $\sim 25\sigma$ is detected at the pulsar position (with a point source integration radius of $0.14°$). The entire VHE excess within a radius of $0.3°$ is 3481 ± 129 photons. Figure 1 shows the excess map of γ-ray candidates above ∼900 GeV, imposed to reduce the H.E.S.S. point spread function (PSF). This map is convolved by a Gaussian of $\sigma = 0.04°$ in order to smooth the statistical fluctuations. The VHE morphology is clearly elongated in the NW-SE direction and is coincident with part of the soft X-ray emission as seen by ROSAT [21]. The intrinsic extension (standard deviations of a Gaussian, deconvolved from the PSF) of this excess are about $6.5'$ and $2.5'$ along the major and minor axis, respectively. The Gaussian centroid is significantly displaced from the pulsar position.

This result provides the first detection of extended emission from a PWN in the VHE band. Assuming that the H.E.S.S. signal arises from IC scattering of target photons by leptons responsible for the X-ray emission via the synchrotron process, the VHE morphology gives more direct information on the spatial distribution of leptons than the X-ray signal. The X-ray morphology results from the convolution of the spatial distribution of these particles with that of the magnetic field, which is thought to be non-uniform within the PWN.

The energy spectrum of this excess is well fitted by a pure power law ($dN/dE \propto E^{-\Gamma}$) up to ∼40 TeV with a spectral index of $\Gamma = 2.27 \pm 0.03_{\rm stat} \pm 0.20_{\rm syst}$. The differential flux at 1 TeV is $(5.7 \pm 0.2_{\rm stat} \pm 1.4_{\rm syst}) \times 10^{-12}$ TeV^{-1} cm^{-2} s^{-1} and the integral flux above 280 GeV represents ∼15% of the Crab nebula flux above the same threshold. The measured runwise integral fluxes are compatible with constant emission. Figure 2-a shows the spectral energy distribution (SED) of the whole PWN with measurements in radio by ATCA [10] and in X-rays by BeppoSAX [17]. This SED can be reproduced by a simple one-zone IC model. A population of non-thermal electrons with a broken power law spectrum produces synchrotron emission in an assumed uniform magnetic field (B) and IC emission on seed photons (CMBR and the local Galactic IR background from [20]). The energy density of IR photons is kept free in order to deal with possible local variations. The electron spectrum and B are adjusted such that the computed photon spectrum matches the experimental data. The best fit model is represented by the lines in Fig. 2-a. It reproduces the SED well, with $B \sim 17\,\mu$G and a spectral index of radiating electrons in the VHE range of $\Gamma_e \sim 2.9$. IR seed photons at $\sim 100\,\mu$m (from dust) with an energy



(a) (b)

Figure 2. Spectral energy distributions of (a) MSH 15-52 and (b) G 0.9+0.1. The references of radio and X-ray spectra are given in the text. The lines are the best model fit of the one zone IC model described in Section 2.

density of $\epsilon(100\,\mu\mathrm{m})\sim 2.5\,\mathrm{eV\,cm^{-3}}$ are needed to reproduce the H.E.S.S. spectrum. This density of photons may be produced by the nearby shell of G 320.4-1.2 [9].

3. Observations of G 0.9+0.1

G 0.9+0.1 is also a composite SNR in radio and X-rays with a shell and compact central emission. This object is situated close to the Galactic Centre (GC), such that its distance is believed to be ~8.5 kpc. An age of a few thousand years is estimated from the radio shell size [13]. Despite the fact that no pulsar has been firmly discovered, the central emission is thought to be from a PWN. Indeed, its X-ray emission exhibits a spectral index softening with increasing radius [19], which is characteristic of such a source.

This object has been observed by H.E.S.S. during the 2004 observation campaign of the GC [3]. The total observation time is ~50 hours and the average energy threshold is ~170 GeV. An excess of 370±28 photons with a significance of $\sim 13\sigma$ is detected. The signal distribution is consistent with point-source emission from the centre of G 0.9+0.1 and disfavours emission from the shell.

The energy spectrum of this excess is consistent with a pure power law with an index of $\Gamma = 2.40 \pm 0.11_{\,\mathrm{stat}} \pm 0.20_{\,\mathrm{syst}}$. The differential flux at 1 TeV is $(8.85 \pm 0.78_{\,\mathrm{stat}} \pm 1.77_{\,\mathrm{syst}}) \times 10^{-13}\,\mathrm{TeV^{-1}\,cm^{-2}\,s^{-1}}$. The emission appears to be steady within statistics and the corresponding integral flux above 200 GeV represents ~2% of the Crab nebula flux above the same threshold, and is the weakest flux ever detected from a PWN in the VHE range. The SED of this source is shown in Fig. 2-b with radio [11] and X-ray [19] data,with the best fit IC model described in Section 2. This SED is well reproduced with this simple leptonic model. The fitted parameters are $B \sim 6\,\mu\mathrm{G}$, $\Gamma_e \sim 2.9$ and $\epsilon(1\,\mu\mathrm{m}) \sim 5.5\,\mathrm{eV\,cm^{-3}}$ for IR seed photons at $\sim 1\,\mu\mathrm{m}$ (from starlight). This high energy density of starlight photons may not be implausible given the central location of G 0.9+0.1 within the Milky Way.

4. Observations of the central part of the Vela SNR

The Vela region contains several interesting VHE candidates (e.g. [5]). Here we report the H.E.S.S. observations of the central 2° of the Vela SNR, around the Vela Pulsar (PSR B0833–45). A compact PWN of $\sim 2'$ diameter has been detected in radio and X-rays around the pulsar (see [18] and the references within) and an extended nebula up to $r \sim 15'$ has been detected in the range 3–10 keV [15]. In soft X-rays (0.9–2.0 keV), a jet-like feature of diffuse emission has been detected by ROSAT [16], which is spatially coincident with a radio filament of Vela X [8]. However, the nature (thermal or not) of this X-ray feature is unclear. The age and the distance of Vela X are estimated to ∼11000 years and ∼300 pc, respectively.

This region has been observed in 2004 and 2005 for ∼23 hours, at an average energy threshold of ∼260 GeV. An extended excess at $\sim 21\sigma$ has been detected with 1774±84 γ-ray candidates within a radius of $r=0.6°$ centered on ($8^{h}35^{m}$, $-45°36'$). This new VHE source, HESS J0835–456, is situated to the south of the X-ray PWN as seen by Chandra and no signal is detected at the pulsar position. The detailed morphology of the γ-ray excess is still under study, as is the spectral energy distribution. The integral flux is estimated to be $\sim 50\%$ of that of the Crab nebula above 1 TeV. The flux upper limit at the 99.9% confidence level around the pulsar position ($r \leq 0.11°$ for a point source) is $2.3 \times 10^{-12}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ above 260 GeV assuming a power law index of $\Gamma=2.6$. The nature of this new VHE source is still unclear, but HESS J0835–456 could possibly be the asymmetric PWN powered by the Vela pulsar.

5. Conclusions

Three new VHE sources have been detected by H.E.S.S. within composite SNRs, and are probably associated with PWN. MSH 15-52 is the first extended PWN detected in the VHE band, while H.E.S.S. signal from G 0.9+0.1 is the weakest PWN emission ever detected at these energies. The new source HESS J0835–456 is an extended object plausibly associated with the Vela X region, which is most likely the extended PWN of the Vela pulsar. Assuming a leptonic scenario and using X-ray data, the VHE emission of MSH 15-52 and G 0.9+0.1 can be reproduced by IC emission on IR seed photons. Finally, it should be noted that other H.E.S.S. sources detected during the scan of the inner part of the Galactic Plane may be also associated with PWN [6].

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