Detection of SN 1006 in VHE γ-rays by H.E.S.S.

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***Abstract*. The historic shell-type supernova remnant SN 1006 is a prime target for observations with Cherenkov telescopes ever since non-thermal synchrotron X-ray emission was discovered in the rims of its 30'-diameter shell. Since theoretical predictions on its TeV-luminosity were only a factor of 2 or 3 below the H.E.S.S. upper limit published in 2005, more in-depth observations of this source were carried out. In 130 h of data accumulated over the years 2003 to 2008, H.E.S.S. finally detected a gamma-ray excess from the remnant of SN 1006, with a flux level well below any previous upper limit. Latest results on the morphology of the TeV gamma-ray and non-thermal X-ray emission will be presented and the implications on the origin of the signal will be discussed.**

***Keywords*: gamma-ray observations, supernova remnants, SN 1006**

I. Introduction

SN 1006 (G327.6+14.6) is the remnant of a galactic type Ia supernova explosion which has been historically recorded by Chinese and Arab astronomers. Presumably, SN 1006 is already in the Sedov phase and expands into the ambient insterstellar medium. The gas density of the ISM is a key parameter for the hydrodynamic evolution of the remnant. Due to its origin as type Ia supernova and also its isolated position of about 500 pc above the galactic plane, the surrounding medium is expected to be unaltered by the progenitor. The most reliable estimate of its distance is 2.2 kpc [1].

Radio and X-ray observations of the remnant show a spherical symmetry with enhanced emission towards the NE and SW limbs. Thermal X-ray (line) emission was detected in the interior of the SNR [2], whereas synchrotron emission by accelerated electrons dominates in the two bright NE and SW limbs [3]. Moreover, arcsecond resolution images by Chandra reveal the small-scale structure of nonthermal X-ray filaments in the NE shell of SN 1006 [4]. These bright X-ray arcs trace the presence of strong shock fronts, where particle acceleration is most likely to occur.

Gamma-ray observations of SN 1006 were carried out by ground-based gamma-ray telescopes. A TeV γ-signal at the level of the Crab flux was claimed by the CANGAROO-I [5] and CANGAROO-II [6] telescopes but subsequent stereoscopic observations of the source with the H.E.S.S telescopes in 2003 and 2004 found no evidence of TeV γ-ray emission, thus deriving an upper limit [7] of $\Phi(> 0.26\ \text{TeV}) < 2.39 \times 10^{-12}$ ph cm^{-2} s^{-1}. Further observations resumed by the CANGAROO-III 4-telescope array could not confirm the previous signal, thereby establishing an upper limit [8] of $\Phi(> 0.5\ \text{TeV}) < 3 \times 10^{-12}$ ph cm^{-2} s^{-1}, which is consistent with the limit given by H.E.S.S.

In the following, we present preliminary analysis results from deeper very high energy (VHE) γ-ray observations of SN 1006 by H.E.S.S.

II. H.E.S.S. observations and results

A. Data-set and analysis methods

H.E.S.S. is an array of imaging atmospheric Cherenkov telescopes situated in the Khomas Highland of Namibia at 1800 m a.s.l. [9]. First observations on SN 1006 started as early as 2003 with an array of two telescopes only and were continued in 2004 with the complete set of four telescopes. Deeper observations followed in the years 2006 – 2008. All observations have been performed in runs of 28 min duration in the moonless part of the nights in the so-called *wobble* mode. In this mode, the telescopes are pointed to an alternating offset position of $\pm 0.5^{\circ}$ in right ascension or declination with respect to the nominal source position, thereby allowing for a simultaneous background monitoring.

The data-set, selected according to standard quality criteria, has a dead-time corrected exposure (live-time) of 130 h and a mean zenith angle of 20°. The data-set was analysed using two different reconstruction algorithms: the Model analysis [10] and the 3D Model analysis [11]. The first analysis method uses raw shower images which are adjusted to a precalculated model through a log-likelihood minimisation. Through a careful treatment of the night sky background pixel per pixel and image cleaning the Model Analysis achieves a better background suppression than more conventional techniques, thus leading to an improved sensitivity. Therefore, all the results presented in the following were obtained using the Model analysis. In order to avoid trials, the analysis was performed on two pre-defined regions selected from XMM-Newton observations[3] in the non-thermal energy band, yielding a detection significance of 9.3 sigma for the NE region and 8.7 sigma respectively for the SW region.

B. Morphology

Fig.1 shows the H.E.S.S. excess map with a charge threshold of 200 photoelectrons (pe) overlayed with the XMM-Newton flux map in the 2 – 4.5 keV energy band which has been smoothed according to the H.E.S.S. point spread function. The striking correlation between γ and X-ray emission regions is confirmed when looking at the radial and azimuthal profiles derived from uncorrelated excess maps. Fig. 2 left shows the radial profiles of H.E.S.S. and adapted XMM-Newton excess events featuring a shell radius of $0.24° \pm 0.014°$ and the width of the radial distribution is $0.076° \pm 0.014°$, which is consistent with the H.E.S.S. point spread function, thereby showing that the emission region is compatible with a thin rim.

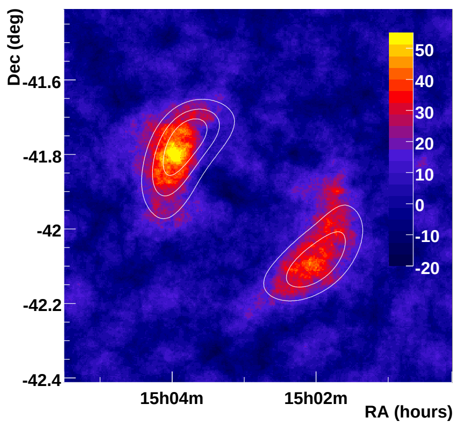

Fig. 1: *H.E.S.S. gamma-ray image of SN 1006. The linear colour scale is in units of excess counts per* $\pi \times (0.1°)^2$*. The white contours correspond to the XMM-Newton flux map in the 2 – 4.5 keV energy range, which has been adapted to the H.E.S.S. point spread function.*

C. Spectral analysis

The spectra for the N.E. and S.W. regions (see Fig.3), obtained with a charge threshold of 60 pe, are compatible with pure power laws yielding similar indices and fluxes (Tab.I). These fluxes correspond to less than 1% of that from the Crab Nebula, well below the previously published H.E.S.S. upper limits [7], thus making SN 1006 one of the faintest known TeV sources so far.

Region	Γ	$\Phi(> 1\text{TeV})$ $(10^{-12}\text{cm}^{-2}\text{s}^{-1})$
NE	$2.36 \pm 0.1_{stat} \pm 0.2_{syst}$	0.155 ± 0.017
SW	$2.43 \pm 0.17_{stat} \pm 0.2_{syst}$	0.133 ± 0.022

TABLE I: *H.E.S.S. spectra for the two regions defined from X-ray observations.*

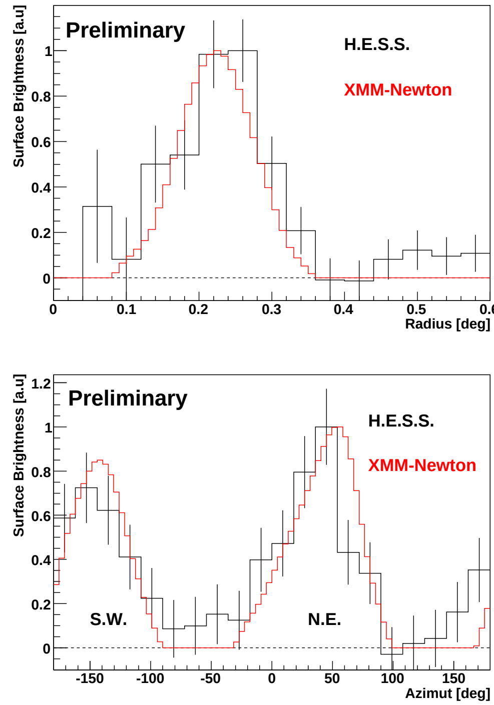

Fig. 2: *Radial profile around the centre of the SNR (15h3m4.56s, -41d55'46.2") obtained from H.E.S.S. data and smoothed XMM-Newton data in the 2 - 4.5 keV energy band.*

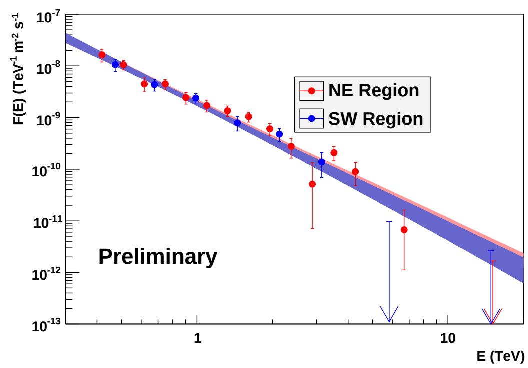

Fig. 3: *Differential energy spectra of SN 1006 extracted from the two regions NE and SW.*

III. Discussion

If the gamma-ray emission is solely due to inverse Compton scattering, constraints can be obtained on the magnetic field B in the acceleration region by comparing the X-ray and gamma-ray fluxes. In this case, the same population of electrons is the cause of both, the synchrotron emission of typical energy ϵ_{keV} in the X-ray band and the high-energy gamma-rays of typical energy E_{TeV}. The X-ray flux between 0.1 keV and 2 keV as measured by Allen et al. [12] is $\Phi_X([0.1 \text{ keV}, 2 \text{ keV}]) = 1.42 \times 10^{-10}\text{erg cm}^{-2}\text{s}^{-1}$. The preliminary gamma-ray energy flux as measured by H.E.S.S. between 0.4 TeV and 20 TeV is $\Phi_\gamma([0.4 \text{ TeV}, 20 \text{ TeV}]) = 1.8 \times 10^{-12}$erg cm^{-2}s^{-1}, which in the inverse Compton scenario leads to a magnetic field of B of about 30 μG.

In the case of the π^0 origin hypothesis, the gamma-ray flux is assumed to be the result of the total energy injected into cosmic rays, essentially protons. Assuming that the proton spectrum below 0.4 TeV can be described by a power law with a spectral index of 2.1, the amount of energy stored in protons can then be estimated on the basis of the total γ-ray luminosity, the characteristic cooling time due to pion production and the density of the ambient medium. Considering the recently measured gas density by Acero et al. [13] of 0.05 particles per cm^3, it is found that the energy injected into protons is approximately 1.8×10^{50} erg.

IV. Conclusion

The detection of VHE gamma-rays from SN 1006 by H.E.S.S. has been confirmed by two independent analysis methods. The measured flux is of order 1% that detected from the Crab Nebula and therefore compatible with the previously published upper limit [7]. The bimodal morphology apparent in gamma-rays is compatible with the non-thermal emission regions visible also in X-rays. As the thickness of the TeV-shell is compatible with a thin rim emission, particle acceleration in the very narrow X-ray filaments, which have been identified as shock waves, is likely to be at the origin of the gamma-ray signal too. Given the measured flux level, the origin of the gamma-ray signal can be accommodated with both inverse Compton and π^0 production, as it leads to a reasonable magnetic field in the leptonic assumption and an acceptable energy budget for cosmic ray acceleration in the hadronic scenario.

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