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Search for Very-High-Energy Gamma-Ray Emission from Young Supernovae with H.E.S.S.

Dirk Lennarz[1,2] for the H.E.S.S. collaboration

[1] *Max-Planck-Institut für Kernphysik, P.O. Box 103980, D 69029 Heidelberg, Germany*
[2] *now at: School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, Georgia, USA*

dirk.lennarz@gatech.edu

Abstract: Supernova (SN) remnants are a well motivated candidate for the acceleration sites of cosmic rays with energies up to the knee (10^{15} eV). It has been suggested that also young SNe ($\lesssim 1$ year after the explosion) may be able to accelerate cosmic rays to even higher energies. A smoking gun for cosmic-ray acceleration in young SNe would be the production of very-high-energy (VHE, > 100 GeV) gamma-ray radiation. The H.E.S.S. imaging air Cherenkov telescope array is an instrument sensitive to such radiation. In this contribution, the pointing directions of the H.E.S.S. telescopes are compared to a recently published, extragalactic SN catalogue to identify coincidental observations. The results of the data analysis are discussed.

Keywords: H.E.S.S., supernovae, very-high energy, gamma rays

1 Introduction

A core collapse at the end of the lifetime of a massive star leads to a supernova explosion (SN). The idea that those events might be connected to cosmic rays was suggested very early [1] and can be convincingly justified from the SN energetics [2]: an acceleration efficiency of $\sim 1\%$ would already be enough to sustain the cosmic ray energy density in our Galaxy. Diffusive shock acceleration is an efficient acceleration mechanism for cosmic rays in SN remnants (SNRs). SNRs may be able to accelerate protons up to energies in the range of 10^{15} eV, but it remains unclear if that is sufficient to explain all Galactic cosmic rays up to the *ankle* around $10^{18.5}$ eV.

There is reason to believe that "young" SNe ($\lesssim 1$ year after the explosion) might be able to accelerate cosmic rays to energies higher than 10^{15} eV. A possible scenario includes the energy release of a compact object (e.g. a pulsar) that forms as a result of a core-collapse SN which can accelerate particles with great efficiency to relativistic energies (internal acceleration). After the SN shock has left the stellar envelope, it starts to interact with the circumstellar material and continues as an external shock. In the external acceleration scenario, the compression of the gas at the shock front creates a reverse (or internal) shock and diffusive shock acceleration might be more efficient in a thin shell between the two shock fronts than at a single shock. This scenario has very successfully reproduced the radio emission of several SNe [3, 4].

It has been realised that in both scenarios very-high-energy (VHE, > 100 GeV) gamma-ray and neutrino radiation might be used as evidence for particle acceleration [5, 6]. The characteristic time-scale of the emission is one year after the explosion. There has been a search for TeV neutrino radiation with data from the AMANDA neutrino telescope [7, 8]. No indication of a signal has been seen and the limits lie at the upper end of the theoretically motivated parameter range and thus only marginally constrain the assumed model.

2 H.E.S.S. Supernova Observations

2.1 The High Energy Stereoscopic System

H.E.S.S., located 1800 m above sea level in the Khomas Highland of Namibia, consists of four Imaging Atmospheric Cherenkov Telescopes [9]. It is sensitive to VHE gamma rays between hundreds of GeV to tens of TeV by detecting Cherenkov light emitted when a gamma ray is absorbed in the atmosphere in an extensive air shower. Each telescope has ~ 100 m^2 tessellated mirror surface and features a pixelated camera of 960 photomultiplier tubes (PMTs). Each pixel corresponds to approximately 0.16° of the sky, resulting in a total field of view of 5° in diameter. Due to the large field of view, young SNe are observed serendipitously during the observation of other targets. The angular resolution (68% containment) of H.E.S.S. is typically 0.1° and the energy resolution $\sim 15\%$.

2.2 A Unified Supernova Catalogue

Suitable H.E.S.S. observations, with a SN in the field of view, within one year after the SN discovery, are selected using a newly published SN catalogue [10]. This new and unified catalogue includes journal-refereed distances to the host galaxies and therefore allows to replace the redshift based estimate of the distance, which is especially bad for nearby SNe that are most interesting for the current analysis. Furthermore, the unified SN catalogue tries to resolve inconsistencies in the listed information, which enables its use as a meta-catalogue of the current SN catalogues. A subset of high-quality SNe with more reliable information can easily be selected with the meta-data.

H.E.S.S. observations are selected based on the following selection criteria:

- SN within 2.5° of the nominal H.E.S.S. pointing direction,
- observation takes place within one year after the SN discovery date,
- SN with known redshift z and $z < 0.01$.

The angular distance cut is introduced because of possible systematic problems of the H.E.S.S. data analysis at larger

SN	Host galaxy	RA J2000	DEC J2000	Dist. [Mpc]	Type	Disc. date
2004cc	NGC 4568	$12^h36^m34.40^s$	$+11^\circ14'32.8''$	25 ± 3	Ic	2004-06-10
2004cx	NGC 7755	$23^h47^m52.86^s$	$-30^\circ31'32.6''$	26 ± 5	II	2004-06-26
2004gk	IC 3311	$12^h25^m33.21^a$	$+12^\circ15'39.9''$	17 ± 3	Ic	2004-11-25
2004gn	NGC 4527	$12^h34^m12.10^s$	$+02^\circ39'34.4''$	12.6 ± 0.5	Ic	2004-12-01
2006mr	NGC 1316	$03^h22^m42.84^s$	$-37^\circ12'28.5''$	12.6 ± 0.6	Ia	2006-11-05
2007cj	IC 2531	$09^h59^m55.76^s$	$-29^\circ37'03.3''$	29 ± 6	Ia	2007-05-03
2008bk	NGC 7793	$23^h57^m50.42^s$	$-32^\circ33'21.5''$	4.0 ± 0.4	IIP?	2008-03-25
2008bp	NGC 3095	$10^h00^m01.57^s$	$-31^\circ33'21.8''$	29 ± 6	IIP	2008-04-02
2009js	NGC 918	$02^h25^m48.28^s$	$+18^\circ29'25.8''$	16 ± 3	IIP?	2009-10-11

Table 1: List of nearby SNe serendipitously observed by the H.E.S.S. telescopes and relevant data from the unified SN catalogue [10]. A type followed by a question mark means that the SN type is uncertain.

offsets. It has recently been shown that an average offset of 2.0° does not introduce a significant bias [11]. The time cut can e.g. be motivated from some simple, analytical modelling, showing that most of the emission can be expected during the first year [12]. Since the expected flux for an extragalactic SN is low, the distance cut restricts the search to nearby SNe only.

Table 1 contains all SNe found with the search criteria and the relevant information as listed in the unified SN catalogue. Strikingly, the closest SN has a distance below 5 Mpc. The list also contains two SNe of type Ia. According to the acceleration mechanism discussed before, no VHE emission can be expected from them, because SNe of type Ia do not produce a compact object or are expected to have a strong reverse shock due to the lack of circumstellar material. However, the two SNe are investigated as well to explore the possibility of unexpected results.

Radio SNe might indicate that the external acceleration is particular powerful and are therefore prime targets to search for VHE emission. However, only a handful of radio SNe have been observed to date and for most SNe the information whether or not it is a radio SN is not available.

2.3 Analysis

The data calibration, image cleaning, Hillas moment calculation and event reconstruction [9] is done using the standard H.E.S.S. analysis software[1]. The background caused by cosmic ray showers is rejected using the cuts for the “hard” configuration [9], enhanced by boosted decision trees [13]. This tight selection is used because the expected fluxes for extragalactic SNe are low. It also determine the optimal size of the signal region (“on-region”) around the SN position. A background estimate is obtained from regions in the same field of view (“off-regions”) using the reflected-region-background model [14].

2.4 Results

Table 2 shows the preliminary results of the analysis of all available H.E.S.S. data with good hardware status. No significant emission from any individual SN is observed. It is striking that except for SN 2006mr, which is a type Ia SN and therefore no VHE emission is expected, all SNe have a positive significance. Figure 1 shows the significance distribution for the core-collapse SNe and a comparison to a Gaussian with mean zero and width one indicates a slight offset between the two. The individual core-collapse SNe have also been stacked, using also those where the significance cannot be calculated. This analysis yields a significance of 3.2, which hints at the indication of emission. A large contribution to the possible signal comes from SN 2004cx and SN 2004gn.

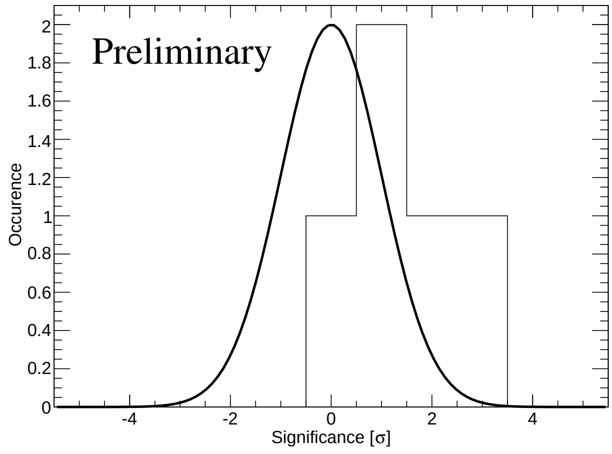

Figure 1: Significance distribution obtained from the number of excess photons for the H.E.S.S. SN observations of core-collapse SNe (excluding SN 2006mr). To guide the eye a Gaussian with mean zero and width one is added.

The results have been crosschecked with an independent calibration and analysis of the data [16]. In the cross-check analysis the significance for SN 2004cx and SN 2004gn is 0.2 and -0.6, respectively. Furthermore, the results have also been cross-checked using the H.E.S.S. standards cuts enhanced by boosted decision trees, which should be less sensitive than the hard cuts. In the cross-check analysis the significance drops to 2.2 for SN 2004cx and -0.3 for SN 2004gn. Stacking the results of the analysis of all SNe with standards cuts yields a total significance of 1.5.

Given the results of the cross-check analyses it appears that the indication of emission seen in the current analysis is most likely a statistical fluctuation and the results are still compatible with the assumption of no signal. Following the individual non-detections, upper limits on the fluxes are calculated for an E^{-2} spectrum (see Table 3). For the H.E.S.S. spectral analysis only observations taking during good weather conditions are used to avoid possible biases in the energy reconstruction.

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[1] version hap-12-06-pl03

SN	Exp. [h]	Offset [°]	Delay [d]	N_{on}	N_{off}	α	N_{excess}	Significance
2004cc	26.0	1.9	287	79	3860	0.019	4	0.5
2004cx	68.8	2.2	176	85	4237	0.015	20	2.4
2004gk	26.0	1.4	119	114	3764	0.027	11	1.1
2004gn	7.5	1.5	127	44	1175	0.024	15	2.6
2006mr	17.8	1.2	320	24	669	0.043	-5	-0.9
2007cj	4.3	2.4	143	3	133	0.014	1	—
2008bk	10.7	1.9	142	14	588	0.020	3	0.7
2008bp	4.8	2.1	277	4	222	0.017	0.3	—
2009js	3.8	2.1	14	8	359	0.016	2	—

Table 2: Preliminary results of the search for excess photons for the H.E.S.S. SN observations. The column "Exp." gives the deadtime corrected livetime of the used observations, the columns "Offset" and "Delay" the average offset of the SN from the nominal observation position and the average number of days between the observations and the discovery date of the SN. N_{on} is the number of gamma-ray candidates in the signal region around the SN position and N_{off} the background estimate. When scaled by the normalisation factor α they yield the number of excess events $N_{\text{excess}} = N_{\text{on}} - \alpha N_{\text{off}}$. The significance is estimated using Eq. (17) of [15], which is only applicable when there are at least 10 counts in the signal region.

SN	Exp. [h]	Offset [deg]	Delay [d]	E_{th} [TeV]	Flux ULs > 1 TeV [$10^{-13}\text{cm}^{-2}\text{s}^{-1}$]
2004cc	21.8	1.9	288	0.62	1.8
2004cx	42.1	2.3	197	0.42	2.3
2004gk	21.8	1.4	120	0.62	1.7
2004gn	7.5	1.5	127	0.46	4.1
2006mr	2.0	2.0	334	0.51	4.9
2007cj	4.3	2.4	143	0.62	12.0
2008bk	8.1	1.9	136	0.51	4.2
2008bp	4.1	2.1	276	0.46	7.9
2009js	3.8	2.1	14	1.00	12.0

Table 3: Preliminary integral flux upper limits for a confidence level of 95% derived from the H.E.S.S. spectral analysis for an E^{-2} spectrum together with the energy threshold (E_{th}). The first three columns are the same as in Table 2, but now for the observations taken under good weather conditions.

3 Summary

The current analysis shows no significant signs of emission for extragalactic SNe observed serendipitously by the H.E.S.S. telescopes, so young SNe cannot be unexpectedly strong emitters of VHE gamma-ray radiation. The derived limits can be used to derive astrophysical implications for modelling, which are not explored here. However, definite conclusions would need further observational input like e.g. a detection and measurements of the pulsar properties inside the SN remnant or the properties of the circumstellar material. The next generation instruments like CTA, with their improved sensitivity, will have better chances to detect VHE emission from extragalactic, young SNe. For a Galactic SN even the current generation of Cherenkov telescopes might be able to confirme or rule out some of the proposed modelling.

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