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# Primary particle acceleration above 100 TeV in the shell-type Supernova Remnant RX J1713.7–3946 with deep H.E.S.S. observations

D. BERGE[1,2], F. AHARONIAN[2,3], W. HOFMANN[2], M. LEMOINE-GOUMARD[4], O. REIMER[5], G. ROWELL[6], H.J. VÖLK[2], FOR THE H.E.S.S. COLLABORATION

[1] *CERN PH Department, CH-1211 Geneva 23, Switzerland*

[2]*Max-Planck-Institut für Kernphysik, P.O. Box 103980, D-69029 Heidelberg, Germany*

[3]*Dublin Institute for Advanced Studies, 5 Merrion Square, Dublin 2, Ireland*

[4]*Laboratoire Leprince-Ringuet, IN2P3/CNRS, Ecole Polytechnique, F-91128 Palaiseau, France*

[5]*Stanford University, HEPL & KIPAC, CA 94305-4085, USA*

[6]*School of Chemistry & Physics, University of Adelaide, Adelaide 5005, Australia*

*berge@cern.ch*

**Abstract:** The shell-type supernova remnant RX J1713.7–3946 was observed during three years with the H.E.S.S. Cherenkov telescope system. The first observation campaign in 2003 yielded the first-ever resolved TeV gamma-ray image. Follow-up observations in 2004 and 2005 revealed the very-high-energy gamma-ray morphology with unprecedented precision and enabled spatially resolved spectral studies. Combining the data of three years, we obtain significantly increased statistics and energy coverage of the gamma-ray spectrum as compared to earlier H.E.S.S. results. We present the analysis of the data of different years separately for comparison and demonstrate that the telescope system operates stably over the course of three years. When combining the data sets, a gamma-ray image is obtained with a superb angular resolution of 0.06 degrees. The combined spectrum extends over three orders of magnitude, with significant gamma-ray emission approaching 100 TeV. For realistic scenarios of very-high-energy gamma-ray production, the measured gamma-ray energies imply efficient particle acceleration of primary particles, electrons or protons, to energies exceeding 100 TeV in the shell of RX J1713.7–3946.

## Introduction

The energy spectrum of cosmic rays measured at Earth exhibits a power-law dependence over a broad energy range. Starting at a few GeV ($1 \text{ GeV} = 10^9$ eV) it continues to energies of at least $10^{20}$ eV. The power-law index of the spectrum changes at two characteristics energies: in the region around $3 \times 10^{15}$ eV – the *knee* region – the spectrum steepens, and at energies beyond $10^{18}$ eV it hardens again. Up to the knee, cosmic rays are believed to be of Galactic origin, accelerated in shell-type supernova remnants (SNRs) – expanding shock waves initiated by supernova explosions [1]. However, the experimental confirmation of an SNR origin of Galactic cosmic rays is difficult due to the propagation effects of charged particles in the interstellar medium. The most promising way of proving the existence of high-energy

particles in SNR shells is the detection of very-high-energy (VHE) gamma rays ($E > 100$ GeV), produced in interactions of cosmic rays close to their acceleration site [2].

Recently the VHE gamma-ray instrument H.E.S.S. has detected two shell-type SNRs, RX J1713.7−3946 [3, 4] and RX J0852.0–4622 [5, 6]. The two objects show an extended morphology and exhibit a shell structure, as expected from the notion of particle acceleration in the expanding shock fronts. While it is difficult to attribute the measured VHE gamma rays unambiguously to nucleonic cosmic rays (rather than to cosmic electrons), the measured spectral shapes favour indeed in both cases a nucleonic cosmic-ray origin of the gamma rays [4, 6].

Apart from the first unambiguous proof of multi-TeV particle acceleration in SNRs, the question
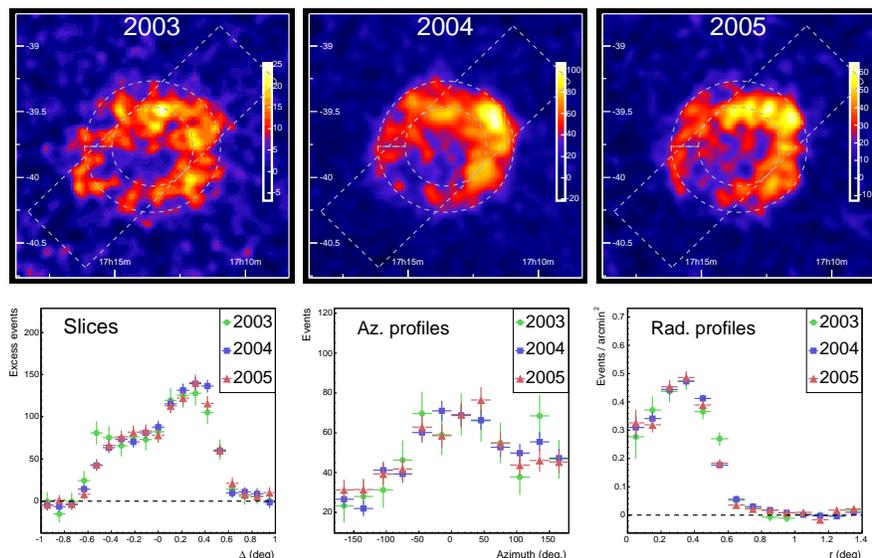
Figure 1: **Upper panel:** H.E.S.S. gamma-ray excess images from the region around RX J1713.7−3946 are shown for three years. **Lower panel:** 1D distributions generated from the non-smoothed, acceptance-corrected gamma-ray excess images.

of the highest observed energies remains an important one. Only the detection of gamma rays with energies of 100 TeV provides experimental proof of acceleration of primary particles, protons or electrons, to the *knee* region (1 PeV). Here we present a combined analysis of H.E.S.S. data of RX J1713.7−3946 of three years, from 2003 to 2005. A comparison of the three data sets demonstrates the expected steady emission of the source as well as the stability of the system. Special emphasis is then devoted to the high-energy end of the combined spectrum.

## H.E.S.S. observations

The High Energy Stereoscopic System (H.E.S.S.) consists of four identical Cherenkov telescopes that are operated in the Khomas Highland of Namibia. Its large field of view of ≈ 5° make H.E.S.S. the currently best suited experiment in the field for the study of extended VHE gamma-ray sources such as young Galactic SNRs.

The H.E.S.S. observation campaign of RX J1713.7−3946 started in 2003. The data were recorded during the commissioning phase of the telescope system, with 2 out of the 4 telescopes operational. The data set revealed extended gamma-ray emission resembling a shell structure. It was actually the first ever resolved image of an astronomical source obtained with VHE gamma rays. In 2004, observations were conducted with the full telescope array. The H.E.S.S. data enabled analysis of the gamma-ray morphology and the spectrum of the remnant with unprecedented precision. A very good correlation was found between the X-ray and the gamma-ray image. The differential spectrum showed deviations from a pure power law at high energies. The 2005 observation campaign was aiming at extending the energy coverage of the spectrum to as high energies as possible. Therefore the observations were preferentially pursued at zenith angles larger than in the two years before to make use of the drastically increased effective collection area of the experiment at high energies. The analysis of these data are presented in the following (a more detailed discussion of this analysis can be found in [7]).
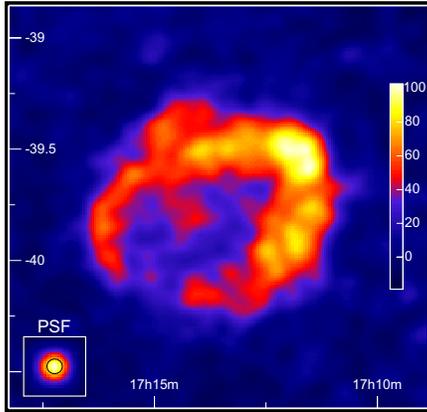
Figure 2: Combined H.E.S.S. image of the SNR RX J1713.7−3946 from the 2004 and 2005 data. A simulated point source (*PSF*) is also shown.

## Analysis results

The analysis techniques used here are presented in detail elsewhere ([8, 9]). The gamma-ray morphology measured in three years is seen in the upper panel of Fig. 1. The images are readily comparable. Very similar angular resolutions are achieved for all years. Good agreement is achieved, as can also be seen from the 1D distributions shown in the lower panel, where also the statistical errors are plotted. Shown from left to right are a slice along a thick box (cf. Fig. 1, upper panel), an azimuthal profile of the shell region, and a radial profile. All the distributions are generated from the non-smoothed, acceptance-corrected excess images. Clearly, there is no sign of disagreement or variability, the H.E.S.S. data of three years are well compatible with each other.

The combined H.E.S.S. image is shown in Fig. 2. Data of 2004 and 2005 are used for this Gaussian smoothed ($\sigma = 2'$), acceptance-corrected gamma-ray excess image. In order to obtain optimum angular resolution, a special high-resolution analysis is applied here. Besides choosing only well reconstructed events, the cut on the minimum event multiplicity is raised to three telescopes, disregarding the 2003 data. Moreover, an advanced reconstruction method is chosen, *algorithm 3* of [10]. The image corresponds to 62.7 hours of observation time. 6702 gamma-ray excess events are measured with a statistical significance

of $48\sigma$. An angular resolution of $0.06°$ ($3.6'$) is achieved. The image confirms nicely the published H.E.S.S. measurements [3, 4], with 20% better angular resolution and increased statistics. The shell of RX J1713.7−3946, somewhat thick and asymmetric, is clearly visible and almost closed. The gamma-ray brightest parts are located in the north and west of the SNR.

The gamma-ray spectra measured with H.E.S.S. in three consecutive years are compared to each other in Fig. 3 (left). In order to compare the data, a correction for the variation of optical efficiency of the telescopes over the years must be applied [11]. After that correction, very good agreement is found. The measured spectral shape remains unchanged over time. The absolute flux levels are well within the systematic uncertainty of 20%. As expected for an object like RX J1713.7−3946, no flux variation is seen on yearly timescales. Clearly, the performance of the telescope system is under good control.

The combined data of three years are shown in Fig. 3 (right). This energy spectrum of the whole SNR region corresponds to 91 hours of H.E.S.S. observations. The combined spectrum extends over almost three decades in energy beyond 30 TeV, and is compatible with previous H.E.S.S. measurements. Taking all events with energies above 30 TeV, the cumulative significance is $4.8\,\sigma$. Different spectral models can be fit to the data. A pure power law is clearly ruled out, alternative spectral models like a power law with exponential cutoff, a broken power law, or a power law with energy-dependent index, all provide significantly better descriptions of the data, but none of these alternative models is favoured over the other.

## Summary

The complete H.E.S.S. data set of the SNR RX J1713.7−3946 recorded from 2003 to 2005 is presented here. Very good agreement is found for both the gamma-ray morphology and the differential energy spectra over the years. The combined analysis confirms the earlier findings nicely: the gamma-ray image reveals a thick, almost circular shell with significant brightness variations. The spectrum follows a hard power law with significant deviations at higher energies (beyond a few TeV).
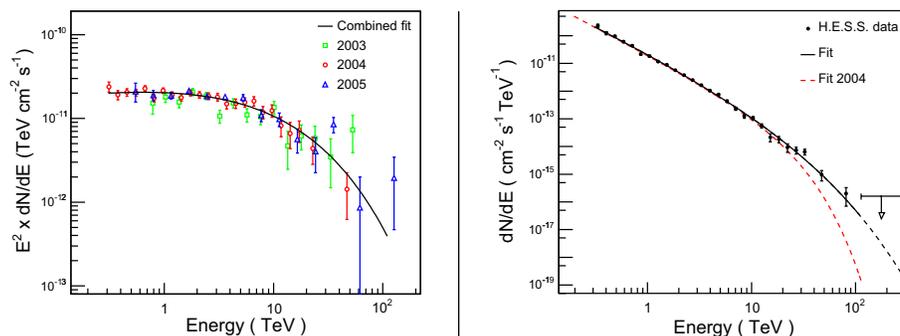
Figure 3: **Left:** Comparison of H.E.S.S. energy-flux spectra of three years. The black curve is the best fit of a power law with exponential cutoff to the combined data, as shown on the **right**, where the combined H.E.S.S. $\gamma$-ray spectrum of RX J1713.7−3946 is shown. The data are well described by the fit function, which is continued as dashed line beyond the fit range for illustration. The arrow is a model-independent upper limit, determined in the energy range from 113 to 300 TeV.

In the combined image using $\sim$ 63 hours of H.E.S.S. observations an unprecedented angular resolution of $0.06°$ is achieved. The high-energy end of the combined spectrum approaches 100 TeV with significant emission $(4.8\sigma)$ beyond 30 TeV. Given the systematic uncertainties in the spectral determination at these highest energies and comparable statistical uncertainties despite the long exposure time, this measurement is presumably close to what can be studied with the current generation of imaging atmospheric Cherenkov telescopes.

From the largest measured gamma-ray energies one can estimate the corresponding energy of the primary particles. In case of $\pi^0$-decay gamma rays, energies of 30 TeV imply that primary protons are accelerated to 30 TeV/0.15 = 200 TeV in the shell of RX J1713.7−3946. On the other hand, if the gamma rays are due to Inverse Compton scattering of VHE electrons, the electron energies at the current epoch can be estimated in the Thompson regime as $E_e \approx 20\sqrt{E_\gamma}$ TeV $\approx 110$ TeV. At these large energies Klein–Nishina effects start to be important and reduce the maximum energy slightly such that $\sim 100$ TeV is a realistic estimate. RX J1713.7−3946 remains an exceptional SNR in respect of its VHE gamma-ray observability, being at present the remnant with the widest possible coverage along the electromagnetic spectrum. The H.E.S.S. measurement of significant gamma-ray emission beyond 30 TeV without indication

of a termination of the high-energy spectrum provides proof of particle acceleration in the shell of RX J1713.7−3946 beyond $10^{14}$ eV, up to energies which start to approach the region of the cosmic-ray *knee*.

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