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## Detection of TeV $\gamma$ -ray emission from the shell-type supernova remnant RX J0852.0–4622 with HESS

F. Aharonian<sup>1</sup>, A. G. Akhperjanian<sup>2</sup>, A. R. Bazer-Bachi<sup>3</sup>, M. Beilicke<sup>4</sup>, W. Benbow<sup>1</sup>, D. Berge<sup>1</sup>, K. Bernlöhner<sup>1,5</sup>, C. Boisson<sup>6</sup>, O. Bolz<sup>1</sup>, V. Borrel<sup>3</sup>, I. Braun<sup>1</sup>, F. Breitling<sup>5</sup>, A. M. Brown<sup>7</sup>, P. M. Chadwick<sup>7</sup>, L.-M. Chounet<sup>8</sup>, R. Cornils<sup>4</sup>, L. Costamante<sup>1,20</sup>, B. Degrange<sup>8</sup>, H. J. Dickinson<sup>7</sup>, A. Djannati-Atai<sup>9</sup>, L. O’C. Drury<sup>10</sup>, G. Dubus<sup>8</sup>, D. Emmanoulopoulos<sup>11</sup>, P. Espigat<sup>9</sup>, F. Feinstein<sup>12</sup>, G. Fontaine<sup>8</sup>, Y. Fuchs<sup>13</sup>, S. Funk<sup>1</sup>, Y. A. Gallant<sup>12</sup>, B. Giebels<sup>8</sup>, S. Gillissen<sup>1</sup>, J. F. Glicenstein<sup>14</sup>, P. Goret<sup>14</sup>, C. Hadjichristidis<sup>7</sup>, M. Hauser<sup>11</sup>, G. Heinzlmann<sup>4</sup>, G. Henri<sup>13</sup>, G. Hermann<sup>1</sup>, J. A. Hinton<sup>1</sup>, W. Hofmann<sup>1</sup>, M. Holleran<sup>15</sup>, D. Horns<sup>1</sup>, A. Jacholkowska<sup>12</sup>, O. C. de Jager<sup>15</sup>, B. Khélifi<sup>1</sup>, Nu. Komin<sup>5</sup>, A. Konopelko<sup>1,5</sup>, I. J. Latham<sup>7</sup>, R. Le Gallou<sup>7</sup>, A. Lemièrè<sup>9</sup>, M. Lemoine-Goumard<sup>8</sup>, N. Leroy<sup>8</sup>, T. Lohse<sup>5</sup>, J. M. Martin<sup>6</sup>, O. Martineau-Huynh<sup>16</sup>, A. Marcowith<sup>3</sup>, C. Masterson<sup>1,20</sup>, T. J. L. McComb<sup>7</sup>, M. de Naurois<sup>16</sup>, S. J. Nolan<sup>7</sup>, A. Noutsos<sup>7</sup>, K. J. Orford<sup>7</sup>, J. L. Osborne<sup>7</sup>, M. Ouchrif<sup>16,20</sup>, M. Panter<sup>1</sup>, G. Pelletier<sup>13</sup>, S. Pita<sup>9</sup>, G. Pühlhofer<sup>1,11</sup>, M. Punch<sup>9</sup>, B. C. Raubenheimer<sup>15</sup>, M. Raue<sup>4</sup>, J. Raux<sup>16</sup>, S. M. Rayner<sup>7</sup>, A. Reimer<sup>17</sup>, O. Reimer<sup>17</sup>, J. Ripken<sup>4</sup>, L. Rob<sup>18</sup>, L. Rolland<sup>16</sup>, G. Rowell<sup>1</sup>, V. Sahakian<sup>2</sup>, L. Saugé<sup>13</sup>, S. Schlenker<sup>5</sup>, R. Schlickeiser<sup>17</sup>, C. Schuster<sup>17</sup>, U. Schwanke<sup>5</sup>, M. Siewert<sup>17</sup>, H. Sol<sup>6</sup>, D. Spangler<sup>7</sup>, R. Steenkamp<sup>19</sup>, C. Stegmann<sup>5</sup>, J.-P. Tavernet<sup>16</sup>, R. Terrier<sup>9</sup>, C. G. Théoret<sup>9</sup>, M. Tluczykont<sup>8,20</sup>, G. Vasileiadis<sup>12</sup>, C. Venter<sup>15</sup>, P. Vincent<sup>16</sup>, H. J. Völk<sup>1</sup>, and S. J. Wagner<sup>11</sup>

<sup>1</sup> Max-Planck-Institut für Kernphysik, Heidelberg, Germany; <sup>2</sup> Yerevan Physics Institute, Armenia; <sup>3</sup> Centre d’Étude Spatiale des Rayonnements, CNRS/UPS, Toulouse, France; <sup>4</sup> Universität Hamburg, Institut für Experimentalphysik, Germany; <sup>5</sup> Institut für Physik, Humboldt-Universität zu Berlin, Germany, e-mail: komin@physik.hu-berlin.de; <sup>6</sup> LUTH, UMR 8102 du CNRS, Observatoire de Paris, Section de Meudon, France; <sup>7</sup> University of Durham, Department of Physics, UK; <sup>8</sup> Laboratoire Leprince-Ringuet, IN2P3/CNRS, École Polytechnique, Palaiseau, France; <sup>9</sup> APC, Paris, France\*; <sup>10</sup> Dublin Institute for Advanced Studies, Ireland; <sup>11</sup> Landessternwarte, Königstuhl, Heidelberg, Germany; <sup>12</sup> Laboratoire de Physique Théorique et Astroparticules, IN2P3/CNRS, Université Montpellier II, France; <sup>13</sup> Laboratoire d’Astrophysique de Grenoble, INSU/CNRS, Université Joseph Fourier, France; <sup>14</sup> DAPNIA/DSM/CEA, CE Saclay, Gif-sur-Yvette, France; <sup>15</sup> Unit for Space Physics, North-West University, Potchefstroom, South Africa; <sup>16</sup> Laboratoire de Physique Nucléaire et de Hautes Énergies, IN2P3/CNRS, Universités Paris VI & VII, France; <sup>17</sup> Institut für Theoretische Physik, Lehrstuhl IV, Ruhr-Universität Bochum, Germany; <sup>18</sup> Institute of Particle and Nuclear Physics, Charles University, Prague, Czech Republic; <sup>19</sup> University of Namibia, Windhoek, Namibia; <sup>20</sup> European Associated Laboratory for Gamma-Ray Astronomy, jointly supported by CNRS and MPG

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**Abstract.** We report the detection of TeV  $\gamma$ -rays from the shell-type supernova remnant RX J0852.0–4622 with data of 3.2 h of live time recorded with HESS in February 2004. An excess of  $(700 \pm 60)$  events from the whole remnant with a significance of  $12\sigma$  was found. The observed emission region is clearly extended with a radius of the order of  $1^\circ$  and the spatial distribution of the signal correlates with X-ray observations. The spectrum in the energy range between 500 GeV and 15 TeV is well described by a power law with a photon index of  $\Gamma = 2.1 \pm 0.1_{\text{stat}} \pm 0.2_{\text{syst}}$  and a differential flux at 1 TeV of  $\varphi_{1\text{TeV}} = (2.1 \pm 0.2_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ . The integral flux above 1 TeV was measured to be  $\Phi(E > 1\text{TeV}) = (1.9 \pm 0.3_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$ , which is at the level of the flux of the Crab nebula at these energies. More data are needed to draw firm conclusions on the magnetic field in the remnant and the type of the particle population creating the TeV  $\gamma$ -rays.

**Key words.** gamma rays: observations – supernovae: individual: RX J0852.0–4622 (G266.2–1.2)

### 1. Introduction

RX J0852.0–4622 (also called G266.2–1.2) is a young shell-type supernova remnant (SNR) in the line of sight to the

Vela SNR. The observed X-ray emission of RX J0852.0–4622 extends over a roughly circular region with a diameter of  $\sim 2^\circ$  with a brightening towards the north-western, western and southern part of the shell and towards the centre. The observed X-ray spectrum is clearly dominated by a continuum which indicates a non-thermal origin of the emission

\* UMR 7164 (CNRS, Université Paris VII, CEA, Observatoire de Paris).

(Aschenbach 1998; Tsunemi et al. 2000; Slane et al. 2001; Iyudin et al. 2005). Deep X-ray observations with the ASCA, CHANDRA and BeppoSAX satellites revealed a compact source in the central region of RX J0852.0–4622: AX J0851.9–4617.4 (CXOU J085201.4–461753) (Slane et al. 2001; Mereghetti 2001; Pavlov et al. 2001; Kargaltsev et al. 2002). This source has been suggested to be a neutron star, supported by the detection of an coincident H $\alpha$  nebula (Pellizzoni et al. 2002). An association of the neutron star candidate with RX J0852.0–4622 would point to a core-collapse supernova. However, recent X-ray observations suggest that RX J0852.0–4622 is the result of a sub-Chandrasekhar type Ia supernova explosion (Iyudin et al. 2005), which would imply that the compact object is not related to RX J0852.0–4622. Radio observations show only weak emission from the shell and no emission from the centre (Duncan & Green 2000). The age and distance of RX J0852.0–4622 were calculated from the diameter seen in X-rays and the flux of  $^{44}\text{Ti}$  lines to be  $680 \pm 100$  years and  $\sim 200$  pc with upper limits of 1100 years and 500 pc, respectively (Aschenbach et al. 1999; Iyudin et al. 1998). An age between 630 and 970 years was estimated by Tsunemi et al. (2000) based on the observation of Ca lines. These estimates for distance and age would imply that RX J0852.0–4622 is one of the closest supernovae in recent history, whereas Slane et al. (2001) argue that RX J0852.0–4622 might be located near the Vela Molecular Ridge at a much larger distance of 1–2 kpc.

Shell-type SNRs with non-thermal X-ray emission are prime candidates for accelerating cosmic rays up to very high energies (Koyama et al. 1995, 1997; Völk et al. 2005). Their detection in VHE  $\gamma$ -rays is expected to be possible with modern atmospheric Cherenkov telescopes (Drury et al. 1994), and to provide insight into the underlying acceleration mechanisms. So far, only one of these SNRs, RX J1713.7–3946, was detected by two independent experiments (Muraishi et al. 2000; Enomoto et al. 2002; Aharonian et al. 2004) employing the imaging atmospheric Cherenkov technique. The CANGAROO collaboration detected  $\gamma$ -ray emission from the north-western part of the RX J0852.0–4622 SNR (Katagiri et al. 2005). Here we report on the detection of the entire SNR RX J0852.0–4622 by HESS in a short observation campaign.

HESS (High Energy Stereoscopic System) is an array of four imaging Cherenkov telescopes dedicated to the detection of VHE  $\gamma$ -rays with energies above 100 GeV (Benbow 2004). Each telescope has a tessellated mirror with an area of 107 m<sup>2</sup> (Bernlöhr et al. 2003; Cornils et al. 2003) and a camera consisting of 960 photomultiplier tubes (Vincent et al. 2003). The HESS array can detect point sources at flux levels of about 1% of the Crab nebula flux with a significance of  $5\sigma$  in 25 h of observation (Benbow 2004). HESS is currently the most sensitive instrument to observe VHE  $\gamma$ -ray sources. With its angular resolution of better than  $0.1^\circ$  per event and its large field of view ( $5^\circ$ ) it is additionally in an ideal position to unravel the  $\gamma$ -ray morphology of extended sources.

## 2. Data set and analysis technique

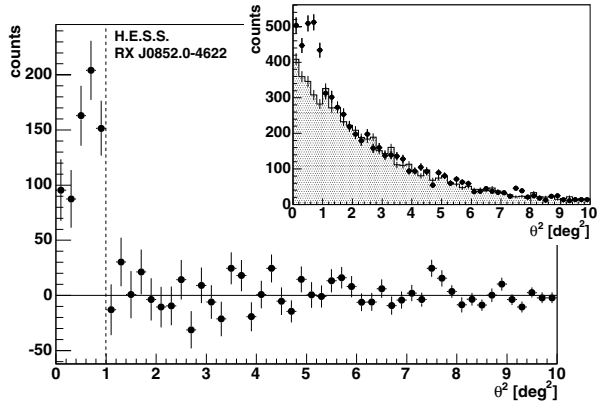
RX J0852.0–4622 was observed by HESS for 4.5 h in February 2004 in standard operation mode using all four telescopes and a trigger requiring the simultaneous observation of an air shower by at least two telescopes (Funk et al. 2004). A run quality selection based on weather conditions and system monitoring was applied. The selected data, which were taken at zenith angles between  $22^\circ$  and  $30^\circ$  with a mean of  $25^\circ$ , represent a dead-time-corrected total exposure time (live time) of 3.16 h. Due to technical problems during data taking, the data of only three telescopes could be included in the analysis.

The background level was estimated from off-source runs, observing sky regions where no  $\gamma$ -ray sources are known. Off-source data were recorded between April and June 2004 at zenith angles between  $13^\circ$  and  $34^\circ$  (mean:  $25^\circ$ ) with a live time of 4.71 h (data set OS1). Another off-source data set (referred to as OS2), taken at a different sky position with less statistics and a possible contamination from a  $\gamma$ -ray source, served to verify the results obtained with OS1. The OS2 data set was recorded between January and March 2004 at zenith angles in the range of  $22^\circ$  to  $32^\circ$  with a mean of  $27^\circ$ . The data of one telescope were excluded from the analysis of both off-source data sets to match the experimental setup of the on-source data set.

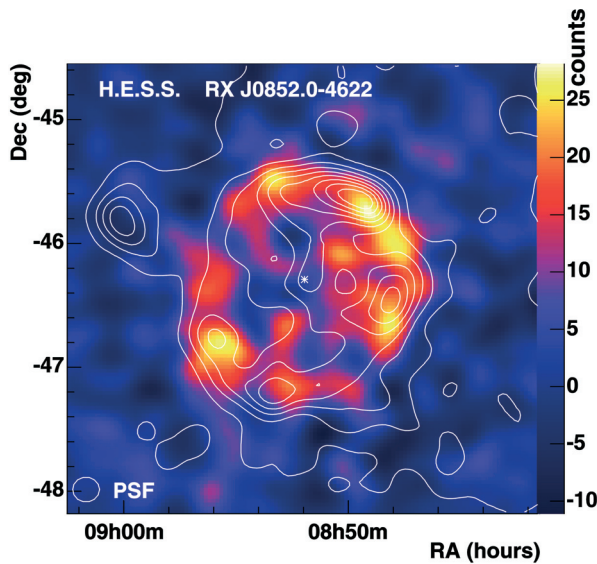
In order to reject most of the low-energy cosmic rays (CR), only camera images with intensities of more than 200 photo electrons were considered for shower reconstruction. For further reduction of the CR background, cuts on scaled image parameters were applied. These cuts were optimised using Monte Carlo simulations for point-like sources with a flux on the level of 10% of the Crab flux. The directions of the air showers were reconstructed from shower images in different cameras and the  $\gamma$ -ray energy was determined from the image intensity and the shower geometry with a typical relative resolution of  $\sim 15\%$ . The energy threshold after all cuts is about 400 GeV. A detailed description of the analysis technique can be found in Aharonian et al. (2005).

## 3. Results

Figure 1 shows the radial distribution of the excess of  $\gamma$ -rays from RX J0852.0–4622 as a function of the reconstructed squared angular distance,  $\theta^2$ , from the nominal centre of the SNR (RA 8h52<sup>m</sup>0, Dec  $-46^\circ 22'$ ). The excess was obtained by subtracting the live-time-normalised background from the on-source data. The inset of Fig. 1 shows good agreement between on-source and off-source data in the range above  $1 \text{ deg}^2$ . The distributions are not flat outside the signal region since the instrument's acceptance drops off towards greater values of  $\theta^2$ . In the region  $\theta^2 \leq 1 \text{ deg}^2$ , approximately corresponding to the X-ray radius of the SNR, a clear excess of  $(700 \pm 60)$  events corresponding to a photon rate of  $(3.7 \pm 0.3) \text{ min}^{-1}$  was found. The significance of the signal is  $12\sigma$ , calculated from 2406 on events and 2541 off events with a normalisation factor of 0.671 using formula (17) of Li & Ma (1983). The  $\theta^2$ -distribution of the excess is much wider than the distribution measured for point-like sources (Aharonian et al. 2005). The source is clearly extended, with a radius of the order of  $1^\circ$ . To address



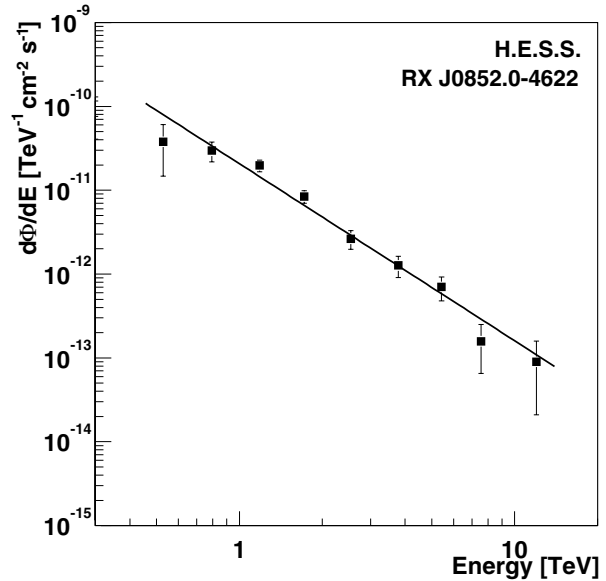
**Fig. 1.**  $\theta^2$ -plot of the excess of  $\gamma$ -ray like events from RX J0852.0–4622, where  $\theta$  is the reconstructed angular distance to the centre of the SNR. The applied  $\theta^2$ -cut of  $1 \text{ deg}^2$  is denoted by the dashed line. The inset shows the on-source data (data points) and off-source data (data set OS1, shaded histogram), normalised using their live-time ratio. The error bars denote  $\pm 1\sigma$  statistical errors.



**Fig. 2.** Count map of  $\gamma$ -rays from the direction of RX J0852.0–4622 after background subtraction. The data are smoothed with a Gaussian ( $\sigma = 0.1^\circ$ ) representing the angular resolution of the instrument. The point spread function (PSF) is indicated by a circle.  $\gamma$ -ray features smaller than the PSF should not be considered as real. The lines denote equidistant contours of smoothed ( $\sigma = 0.1^\circ$ ) X-ray data from the ROSAT All Sky Survey, with energies restricted to above 1.3 keV. The position of the neutron star candidate AX J0851.9–4617.4 is marked with an asterisk. The axes show J2000.0 equatorial coordinates.

the question of emission from a compact central object, the central region of the SNR was tested for the presence of a point-like source by applying a point-source cut ( $\theta^2 \leq 0.02 \text{ deg}^2$ ) around AX J0851.9–4617.4. No significant excess was found; the upper limit (99.9% confidence level) on the integral photon flux above 1 TeV is  $1.3 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ .

A sky map of the excess is displayed in Fig. 2. No correction for the instrument’s acceptance, which drops by 23% towards the source boundary at  $1^\circ$ , was applied. An excess of  $\gamma$ -rays from an extended region is visible. The overlaid contour



**Fig. 3.** Differential photon flux spectrum of the  $\gamma$ -rays from the direction of the whole SNR. The solid line is the result of a power law fit. The error bars denote  $\pm 1\sigma$  statistical errors.

plot was derived from X-ray data taken in scanning mode with the PSPC detector aboard the ROSAT satellite (Voges et al. 1999), restricting the photon energies to above 1.3 keV in analogy to the original detection by Aschenbach (1998). We note that the X-ray data are contaminated with emission from the Vela SNR and RCW 37 (east of RX J0852.0–4622). Ignoring this and the fact that the  $\gamma$ -ray data were not corrected for acceptance and exposure, the correlation coefficient between the  $\gamma$ -ray counts and X-ray counts in bins of  $0.3^\circ \times 0.3^\circ$  size was found to be  $0.67 \pm 0.05$ . The use of ASCA X-ray data (Slane et al. 2001), which does not cover the complete SNR, yields a very similar correlation coefficient. More detailed studies of the  $\gamma$ -ray morphology have to await future high-statistics observations.

The differential photon flux spectrum of the  $\gamma$ -ray emission from the whole SNR is shown in Fig. 3. A power law

$$\varphi(E) = \frac{d\Phi}{dE} = \varphi_{1 \text{ TeV}} \cdot \left( \frac{E}{1 \text{ TeV}} \right)^{-\Gamma}$$

was fitted to the data points (solid line in Fig. 3) with a  $\chi^2/\text{d.o.f.} = 10/7$  and results in a photon index of  $\Gamma = 2.1 \pm 0.1_{\text{stat}}$  and a differential flux at 1 TeV of  $\varphi_{1 \text{ TeV}} = (2.1 \pm 0.2_{\text{stat}}) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ . The corresponding integral flux above 1 TeV is  $\Phi(E > 1 \text{ TeV}) = (1.9 \pm 0.3_{\text{stat}}) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$  which is of the order of the Crab flux at these energies (Masterson et al. 2004). As a cross-check, the analysis was repeated using data set OS2 for background estimation and compatible results were obtained.

Systematic uncertainties were estimated by varying cuts and the binning in the energy spectrum determination, and by repeating the analysis with different background data sets (OS1, OS2 and subsamples of OS1) and with different atmosphere models in the simulation. The systematic errors are  $\sim 0.2$  for the photon index and  $\sim 30\%$  for both the differential flux at 1 TeV and the integral flux.

#### 4. Discussion

RX J0852.0–4622 is the second shell-type SNR which has been spatially resolved at TeV energies, following the HESS detection of RX J1713.7–3946 (Aharonian et al. 2004). Similar to RX J1713.7–3946, RX J0852.0–4622 is a weak radio source and was initially discovered in X-ray observations. There are some other similarities between these two SNRs, in particular: (i) in both sources the non-thermal X-ray component strongly dominates over the thermal component; and (ii) both are strong sources of extended TeV emission spatially correlated with X-rays.

There are two basic mechanisms for TeV  $\gamma$ -ray production in young SNRs – inverse Compton scattering (IC) of multi-TeV electrons on photons of the cosmic microwave background (CMB) and other target photon fields, and  $\pi^0$ -decay  $\gamma$ -rays from inelastic interactions of accelerated protons with ambient gas. The measured  $\gamma$ -ray flux spectrum of RX J0852.0–4622 translates into an energy flux between 1 and 10 TeV of  $w_\gamma(1-10 \text{ TeV}) = \int_{1 \text{ TeV}}^{10 \text{ TeV}} E\varphi(E)dE \approx 7 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ , which is quite close to the X-ray energy flux of the entire remnant of  $w_X(0.5-10 \text{ keV}) \sim 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$  (Slane et al. 2001). If the  $\gamma$ -ray emission is entirely due to the IC process on CMB photons, and assuming that the synchrotron and IC emissions are produced by the same electrons and the emission regions have roughly the same size ( $\xi \approx 1$ ) then, according to  $w_\gamma/w_X \approx 0.1(B/10 \mu\text{G})^{-2}\xi$  (Aharonian et al. 1997), the magnetic field in the  $\gamma$ -ray production region cannot significantly exceed the interstellar value of several  $\mu\text{G}$ . If one assumes a larger magnetic field in the remnant the IC scenario would therefore become less favourable. On the other hand, the TeV flux can be easily explained in terms of interactions of accelerated protons with the ambient gas. The total energy in accelerated protons in the range 10–100 TeV required to provide the observed TeV flux is estimated to be  $W(10-100 \text{ TeV}) \approx t_{pp \rightarrow \pi^0} \times L_\gamma(1-10 \text{ TeV}) \approx 1.5 \times 10^{48} (d/200 \text{ pc})^2 (n/1 \text{ cm}^{-3})^{-1} \text{ erg}$ , where  $t_{pp \rightarrow \pi^0} \approx 4.5 \times 10^{15} (n/1 \text{ cm}^{-3})^{-1} \text{ s}$  is the characteristic cooling time of protons through the  $\pi^0$  production channel, and  $L_\gamma(1-10 \text{ TeV}) = 4\pi d^2 w_\gamma(1-10 \text{ TeV}) \approx 3 \times 10^{32} (d/200 \text{ pc})^2 \text{ erg/s}$  is the luminosity of the source in  $\gamma$ -rays between 1 and 10 TeV. Assuming that the power-law proton spectrum with spectral index  $\alpha \approx \Gamma$  continues down to  $E \sim 1 \text{ GeV}$ , the total energy in protons is estimated to be  $W_{\text{tot}} \approx 10^{49} (d/200 \text{ pc})^2 (n/1 \text{ cm}^{-3})^{-1} \text{ erg}$ . Thus, for distances to the SNR in the order of  $d \approx 200 \text{ pc}$  the conversion of several percent of the assumed mechanical explosion energy of  $10^{51} \text{ erg}$  to the acceleration of protons up to  $\geq 100 \text{ TeV}$  would be sufficient to explain the observed TeV  $\gamma$ -ray flux by nucleonic interactions in a medium of density comparable to the average density of the interstellar medium,  $n \sim 1 \text{ cm}^{-3}$ . For larger distances a correspondingly higher fraction of the explosion energy would have to be converted into the acceleration of protons.

More data will be taken with HESS in order to study the morphology of the remnant in detail, to compare the results with the CANGAROO measurement and to distinguish between electronic and hadronic acceleration scenarios.

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