Localising the VHE $\gamma$-ray source at the Galactic Centre

A.R. Bazer-Bachi, Y. Beckerini, B. Behera, K. Bernlöhr, A. Bochow, C. Boisson, J. Bohmont, V. Borrel, I. Braun, J. Brucker, F. Brun, P. Brun, R. Bühler, T. Bulik, I. Büsching, T. Bouteloup, F.M. Chadwick, A. Charbonnier, R.C. Chaves, C. Cheatham, J. Conrad, M. Cognier, M. Dalton, M.K. Daniel, I.D. Davids, B. Degrange, C. Dell, H.J. Dickinson, A. Djammati-Atai, D. Domiano, L.O’C. Drury, G. Dubus, J. Dyks, M. Dyrdal, K. Ebgerter, P. Eger, P. Espigat, L. Fallou, C. Farnier, S. Fegan, F. Feinstein, A. Fiasson, A. Förster, G. Fontaine, M. Füßling, S. Gabici, Y.A. Gallant, L. Gérard, D. Gerbig, B. Giebels, J.F. Glicenstein, B. Glück, P. Goret, D. Göring, M. Hauser, S. Heinzelmann, G. Henri, G. Hermann, J.A. Hinton, A. Hoffmann, W. Hofmann, P. Hofverberg, M. Holleran, S. Hoppe, D. Horns, A. Jacholkowska, O.C. de Jager, C. Jahn, I. Jung, K. Katarzyński, U. Katz, S. Kaufmann, M. Kerschhaggl, D. Khangulyan, B. Kheîli, D. Kłocko, W. Kluzniak, T. Kneiske, N. Komin, K. Kosack, R. Kossakowski, G. Lamanna, J.-P. Lamègue, T. Lohse, V. Marandon, O. Martinez-Huynh, A. Marcowith, J. Masbou, D. Maurin, T.J.L. McComb, M.C. Medina, J. Méhault, R. Moderski, E. Moulin, M. Naumann-Godo, M. de Naurois, D. Nedbal, D. Nekrassov, B. Nicholas, J. Niemiec, S.J. Nolan, S. Ohm, J.-F. Olive, E. de Oia Wilhelmi, K.J. Orford, M. Ostrowski, M. Panter, M. Paz Arribas, G. Pedaletti, P. Pelletier, P.-O. Petrucci, S. Pita, G. Pühlhofer, M. Punch, A. Quirrenbach, B.C. Rauhenheimer, M. Raue, S.-M. Rayner, O. Reimer, M. Renaud, F. Rieger, J. Ripken, L. Roth, S. Rosier-Lees, G. Rowell, B. Rudak, C.B. Rutten, J. Ruppel, F. Ryle, V. Sahakian, A. Santangelo, R. Schlickeiser, F.M. Schöck, A. Schönwald, U. Schwank, S. Schwarzbarg, S. Schwemmer, A. Shalchi, M. Sikora, J.L. Skilton, H. Sol, L. Stawarz, R. Steenkamp, C. Stegmann, F. Stinzing, G. Superina, I. Sushch, A. Szostek, G. Vasileiadis, C. Venter, L. Venter, J.P. Vialle, P. Vincent, M. Vivier, H.J. Völk, F. Volpe, S.J. Wagner, M. Ward, A.A. Zdziarski, and A. Zech

1 Max-Planck-Institut für Kernphysik, P.O. Box 103980, D 69029 Heidelberg, Germany
2 Yerevan Physics Institute, 2 Alikhanian Brothers St., 375036 Yerevan, Armenia
3 Centre d’Étude Spatiale des Rayonnements, CNRS/UPS, 9 av. du Colonel Roche, BP 4346, F-31029 Toulouse Cedex 4, France
4 Universität Hamburg, Institut für Experimentalphysik, Luruper Chaussee 149, D 22761 Hamburg, Germany
5 Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, D 12489 Berlin, Germany
6 LUTH, Observatoire de Paris, CNRS, Université Paris Diderot, 5 Place Jules Janssen, 92190 Meudon, France
7 IRFU/DSM/CEA, CE Saclay, F-91191 Gif-sur-Yvette, Cedex, France
8 University of Durham, Department of Physics, South Road, Durham DH1 3LE, U.K.
9 Unit for Space Physics, North-West University, Potchefstroom 2520, South Africa
10 Laboratoire Leprince-Ringuet, École Polytechnique, CNRS/IN2P3, F-91128 Palaiseau, France
11 Laboratoire d’Annecy-le-Vieux de Physique des Particules, Université de Savoie, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France
12 Astrophysik und Cosmolgie (APC), CNRS, Université Paris 7 Denis Diderot, 10, rue Alice Domon et Leonie Duquet, F-75205 Paris 13, France
13 Dublin Institute for Advanced Studies, 5 Merrion Square, Dublin 2, Ireland
14 Landessternwarte, Universität Heidelberg, Königstuhl, D 69117 Heidelberg, Germany
15 Laboratoire de Physique Théorique et Astroparticules, Université Montpellier 2, CNRS/IN2P3, CC 70, Place Eugène Bataillon, F-34095 Montpellier Cedex 5, France
16 Universität Erlangen-Nürnberg, Physikalisches Institut, Erwin-Rommel-Str. 1, D 91058 Erlangen, Germany
17 Laboratoire d’Astrophysique de Grenoble, INSU/CNRS, Université Joseph Fourier, BP 53, F-38041 Grenoble Cedex 9, France
18 Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, D 72076 Tübingen, Germany
19 LPNHE, Université Pierre et Marie Curie Paris 6, Université Denis Diderot Paris 7, CNRS/IN2P3, 4 Place Jussieu, F-75252, Paris Cedex 5, France
20 Charles University, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, V Holešovičkách 2, 180 00 Prague, Czech Republic
21 Institut für Theoretische Physik, Lehrstuhl IV: Weltraum und Astrophysik, Ruhr-Universität Bochum, D 44780 Bochum, Germany
The inner 10 pc of our galaxy contains many counterpart candidates of the very high energy (VHE; > 100 GeV) γ-ray point source HESS J1745-290. Within the point spread function of the H.E.S.S. measurement, at least three objects are capable of accelerating particles to very high energies and beyond, and of providing the observed γ-ray flux. Previous attempts to address this source confusion were hampered by the fact that the projected distances between those objects were of the order of the error circle radius of the emission centroid (34′′, dominated by the pointing uncertainty of the H.E.S.S. instrument). Here we present H.E.S.S. data of the Galactic Centre region, recorded with an improved control of the instrument pointing compared to H.E.S.S. standard pointing procedures. Stars observed during γ-ray observations by optical guiding cameras mounted on each H.E.S.S. telescope are used for off-line pointing calibration, thereby decreasing the systematic pointing uncertainties from 20′′ to 6′′ per axis. The position of HESS J1745-290 is obtained by fitting a multi-Gaussian profile to the background-subtracted γ-ray count map. A spatial comparison of the best-fit position of HESS J1745-290 with the position and morphology of candidate counterparts is performed. The position is, within a total error circle radius of 13′′, coincident with the position of the supermassive black hole Sgr A∗ and the recently discovered pulsar wind nebula candidate G359.95-0.04. It is significantly displaced from the centroid of the supernova remnant Sgr A East, excluding this object with high probability as the dominant source of the VHE γ-ray emission.

Key words: Galaxy; centre – ISM: individual: Sgr A East – ISM: individual: Sgr A∗ – ISM: individual: G 359.95-0.04 – gamma-rays: observations

I. VHE γ-RAYS FROM THE GALACTIC CENTRE

Since the discovery of the strong compact radio source Sgr A∗ (Balick & Brown [1974]), the Galactic Centre (GC), as the closest galactic nucleus, has served as a unique laboratory for investigating the astrophysics of galactic nuclei in general. The radio picture (LaRosa et al. [2000]) of the central few 100 pc around the centre of the Milky Way exhibits a complex and very active region, with numerous sources of non-thermal radiation, making this region a prime target for observations at very high energies (VHE; > 100 GeV). Indeed several Imaging Atmospheric Cherenkov Telescopes (IACTs) have detected a source of VHE γ-rays in the direction of the GC (Aharonian et al. [2004, Albert et al. 2006]. Kosack et al. [2004, Tsuchiya et al. [2004]. The H.E.S.S. instrument (see Aharonian et al. [2006a] and references therein) provides the to date most precise VHE data on this source, henceforth called HESS J1745-290. As shown with deep observations in 2004, HESS J1745-290 is a point source for H.E.S.S. (rms spatial extension < 1′′ at 95% CL), and is within 7′′ ± 14′′stat ± 28′′sys positionally coincident with the bright radio source Sgr A∗ (Aharonian et al. [2006b]). The measured energy spectrum does not fit Dark Matter (DM) model spectra – at least for the most popular models of DM annihilation –, ruling out the bulk of the TeV emission soley to be of a DM origin (Aharonian et al. [2006b]).

Of all possible astrophysics counterparts, the 3 × 10^6 M⊙ supermassive black hole (SMBH) coincident with the Sgr A∗ radio position is a compelling candidate. Various models predict VHE emission from this object, produced either close to the SMBH itself (Aharonian & Neronov [2005a]), within an O(10) pc zone around Sgr A∗ due to the interaction of run-away protons with the ambient medium (Aharonian & Neronov [2006])...
Although the X-ray flux increased to Sgr A\textsuperscript{*} (Aharonian et al. 2009). Moreover, during a campaign of H.E.S.S. data collected during the years 2004-2006, no hint for variability, flaring activity, or QPOs has been detected in the VHE \(\gamma\)-ray lightcurve in 93 h live time of H.E.S.S. data collected during the years 2004-2006 (Aharonian et al. 2009). Moreover, during a campaign of simultaneous H.E.S.S. and Chandra observations of Sgr A\textsuperscript{*} in 2005, a major X-ray flare of 1600 s duration was observed. Although the X-ray flux increased to \(\sim 9\) times the quiescent level, no evidence for flaring activity was detected in the VHE lightcurve (Aharonian et al. 2008). This result makes it highly unlikely that X-ray and VHE emission originate from the same source region, and puts constraints on models predicting correlated flaring.

Besides Sgr A\textsuperscript{*} and its immediate vicinity, there are at least two other production site candidates for VHE emission. The first one is the radio-bright, shell-like supernova remnant (SNR) Sgr A East, which surrounds partially Sgr A\textsuperscript{*}. SNRs have been shown to be efficient particle accelerators (see e.g. Helder et al. 2009), and the presence of an \(\mathcal{O}(\text{mg})\) magnetic field (Yusef-Zadeh et al. 1996) makes Sgr A East a compelling candidate for particle acceleration to very high energies (Crocker et al. 2005). The second one is the recently detected pulsar wind nebula (PWN) candidate G359.95-0.04 (Wang et al. 2006). Despite of its faint X-ray flux, it may plausibly emit TeV \(\gamma\)-rays at an energy flux level compatible with the H.E.S.S. observations (Hinton \& Aharonian 2007), assuming that G359.95-0.04 is located at the same distance as Sgr A\textsuperscript{*}.

A firm identification of HESS J1745-290 is particularly hampered by the – compared to radio or X-ray instruments – modest angular resolution of the current generation of Cherenkov telescopes (\(\leq 5'\) for a single \(\gamma\)-ray at TeV energies), which gives rise to source confusion in this densely populated region of the galaxy. Adopting a distance to the GC of 8.33 kpc (Gillessen et al. 2009), the H.E.S.S. source size upper limit encloses a region of about 2.9 pc radius. Comparing this number to the projected distance of Sgr A\textsuperscript{*} to the radio maximum of Sgr A East and the X-ray maximum of G359.95-0.04 (3.7 pc and 0.4 pc, respectively), it becomes clear that a precise position measurement of the centre-of-gravity of HESS J1745-290 can help to shed light on the nature of this source.

Although previous H.E.S.S. position measurements have been unprecedentedly precise, the relatively large – compared to statistical errors – systematic errors due to pointing uncertainties of the H.E.S.S. array rendered the identification of the major contributing source of the VHE emission, and especially a clear statement on the role of Sgr A East, difficult. In this paper a refined measurement of HESS J1745-290’s emission centroid is reported. Using improved telescope pointing control, the systematic error of the measurement is decreased by a factor of three compared to previous results, and the total error on the centroid position is reduced to \(13''\) (68% containment radius), compared to \(34''\) in Aharonian et al. (2006b).

II. ASTROMETRIC POINTING CORRECTIONS

The 12 m mirror dishes of the H.E.S.S. telescopes are supported by altitude/azimuth mounts. During \(\gamma\)-ray observations, all four H.E.S.S. telescopes track the targeted source with a nominal precision of better than a few seconds of arc per axis. However, due to the weight of the mirrors and the Cherenkov cameras, \(\mathcal{O}(\text{mm})\) deflections of the 15 m long camera masts and the mirror dishes make astrometric corrections necessary. The H.E.S.S. pointing corrections are based on the assumption that telescope deformations, and hence pointing deviations, are reproducible, and depend only on the (alt-az) pointing position. They are of the order of a few minutes of arc and are applied to the recorded events after data taking, based on a set of independently recorded calibration data (Gillessen 2004). These standard pointing corrections, by default applied to all H.E.S.S. data, provide a localisation of point-like \(\gamma\)-ray sources with a systematic pointing error of \(20''\) per axis.

The analysis presented here improves significantly upon these systematic uncertainties by utilising optical guiding telescopes mounted on the mirror dish of each H.E.S.S. telescope. Stars within the field of view (\(0.3'' \times 0.5''\)) of the guiding telescopes are imaged by CCD cameras with a projected pixel size of 2''3. The guiding telescope optics is slightly defocused such that the light from each star is imaged onto several CCD pixels, making precise position measurement possible. Positions of recorded stars are then compared to nominal coordinates listed in the Hipparcos and Tycho star catalogues (ESA 1997). For the analysis presented here, images were recorded at a rate of about 1/min and contain typically 2-10 identified stars. Additionally, for each H.E.S.S. telescope, deformations of the Cherenkov camera masts are measured by monitoring eight reference LEDs mounted on the Cherenkov camera body. This is done with the help of CCD cameras installed at the centre of each mirror dish. From the combined information of the two CCD cameras, pointing corrections are calculated for the individual H.E.S.S. telescopes. To correct the direction of each \(\gamma\)-ray, linear interpolation is used between the pointing corrections derived from the individual CCD images. The difference in refraction correction for star light and Cherenkov light from \(\gamma\)-ray showers is taken into account. An absolute calibration of the guiding system is performed at the beginning and end of every moon
period: the telescopes are pointed at typically 50 bright stars uniformly distributed in the sky. Images of the stars are recorded with the guiding telescopes. Additionally, the star light is reflected by the mirrors onto screens in front of the Cherenkov cameras, and images of the stars and of the reference LEDs are recorded with the central CCD cameras. From these measurements altitude and azimuth dependent pointing models are derived. These relate, for any given observation position, the star position measured with the guiding telescopes to the star spot position determined with the central CCD camera.

Typically, the precision pointing corrections derived in this way differ only slightly from the standard pointing corrections. However, the observation of stars and camera body simultaneously to γ-ray collection reduces systematic uncertainties significantly, such as hysteresis effects observed in the camera mast structure, which limit the precision of the altitude determination. Systematic errors due to an observed long-term movement of the telescope foundations are cancelled, as are uncertainties in the absolute positioning of the tracking system. Thermal expansion of the CCD chips due to changes of the ambient temperature is accounted for in the precision pointing model. For the data set presented in this analysis, a total systematic pointing error of ±6′′ per axis on the sky was derived (Braun 2007). Possible systematic effects regarding the reconstruction of the γ-ray shower images, such as an inhomogeneous field-of-view or the effect of Earth’s magnetic field on the image parameters have been studied. No effect was observed that would systematically shift the centroid of point-like γ-ray sources by more than 2′′. Furthermore, the precision pointing corrections were extensively validated on VHE γ-ray data of point-like sources with positions and extensions known from observations at another waveband (with much better pointing accuracy and angular resolution). A detailed description of the precision pointing technique and the estimation of systematic errors is beyond the scope of this letter and will be published elsewhere.

III. ANALYSIS OF Γ-RAY DATA

Since the guiding telescopes for precision pointing corrections are in operation only since 2005, the results reported here are based on 64 h (live time) of data recorded with the H.E.S.S. instrument between May 4 and August 23, 2005, and between April 4 and August 4, 2006. Most of the observations (59 h) were carried out in wobbly mode, i.e. the telescope pointing direction was offset from the target direction (Sgr A∗) by typically 0.5°–0.7° in either right ascension or declination, in an alternating fashion. The remaining 5 h of data were recorded with various offsets of up to 1.4° from the direction of Sgr A∗. The mean zenith angle of the data described here is 23°, and the observation zenith angles range from 6° – 60°.

Data were analysed with the standard H.E.S.S. calibration and reconstruction chain (Aharonian et al. 2006a).

First, each shower image recorded by the Cherenkov cameras was corrected for astrometry using the precision pointing corrections described above. To suppress background events caused by cosmic ray induced air showers, γ-rays were selected based on the shape of the shower images in the Cherenkov cameras, as described by Hillas parameters (Hillas 1985) using hard cuts (Aharonian et al. 2006a). As opposed to standard cuts, hard cuts select high-intensity shower images, reducing further the number of background events (relative to signal) at the expense of a higher energy threshold (∼630 GeV for a mean zenith angle of 23°). In addition, this high-intensity selection leads to a sample of well reconstructed showers, resulting in an improved angular resolution. After this event selection, the direction of each γ-ray was reconstructed by intersecting the major axes of the Hillas ellipses, following algorithm 3 from Hofmann et al. (1999). This approach uses the Hillas width and length of the shower images to estimate the γ-ray direction independently with each telescope. These estimates are then combined to yield the optimum γ-ray direction, which improves upon the standard H.E.S.S. reconstruction in terms of angular resolution. Reconstructed events were accumulated in a 2° × 2° image, centred at the position of Sgr A∗ and binned into squares of 0.03° angular size. Remaining background from cosmic-ray induced showers was estimated using the Ring-Background technique (Berge et al. 2007), excluding regions containing known γ-ray sources, such as the band of diffuse emission along the Galactic Centre ridge (Aharonian et al. 2006d). A background subtraction based on a template approach (Rowell 2003) gives consistent results. An excess of 1313 ± 42 VHE γ-rays is found within a circle of radius 0.1° centred on Sgr A∗, with a statistical significance of 46 standard deviations above the background. The energy spectrum derived from this reduced data set is compatible with that reported in Aharonian et al. (2009), which was obtained with a different analysis chain.

The point spread function (PSF), reflecting the angular extension of a point source seen by the H.E.S.S. instrument, was modeled using Monte-Carlo γ-ray simulations, taking into account the distributions of zenith angle, of offset of the pointing position relative to Sgr A∗, as well as the energy distribution of γ-rays from HESS J1745-290 (Aharonian et al. 2009). The simulated PSF can be well described by the sum of two Gaussian functions with equal mean (Aharonian et al. 2006a). The overall angular resolution of the data set is 3.9′ (68% containment radius).

IV. POSITION OF HESS J1745-290

The centroid of the VHE emission was determined by fitting the acceptance corrected and background subtracted γ-ray count map in a window of ±0.2° centred on Sgr A∗, with a 2-dimensional radially symmetric profile. The fit model was composed of a double-Gaussian
part accounting for the PSF of the H.E.S.S. instrument, convolved with an assumed Gaussian surface brightness distribution to account for a possible intrinsic extension of the source. This source extension and the overall normalisation were left as free parameters in the fit. The PSF was fixed from MC simulations as described above.

Diffuse $\gamma$-ray emission along the Galactic Centre ridge introduces an asymmetric $\gamma$-ray background in the region of Sgr A*, which could in principle bias the position determination of HESS J1745-290. In a circular region of 0.1° around the centroid position, this background is at a level of ≈ 15% of the total flux observed from the source (Aharonian et al. 2006b, 2009). In the position determination, the background $\gamma$-ray diffuse emission was therefore taken into account by adding an independent term in the fit function with free normalisation. The expected diffuse $\gamma$-ray emission was modelled – following Aharonian et al. (2006d) – by a radially symmetric Gaussian distribution of width 0.8° centred at the GC, multiplied with the density distribution of molecular clouds in the region from CS line emission measurements (Tsuboi et al. 1999). The position fit is largely insensitive to details of the diffuse emission model. Indeed, when fitting the position of HESS J1745-290 without taking into account the diffuse component, the result is still consistent within statistical errors with the final position quoted below.

Using a $\chi^2$-minimisation procedure, the best-fit position of HESS J1745-290 in equatorial coordinates is $\alpha = 17^h 45^m 39.6^s \pm 0'.4_{\text{stat}} \pm 0'.4_{\text{sys}}$, $\delta = -29^o 0' 22'' \pm 6''_{\text{stat}} \pm 6''_{\text{sys}}$ (J2000.0). The best-fit probability is 12%. The best-fit position is within $8'' \pm 9''_{\text{stat}} \pm 9''_{\text{sys}}$ coincident with the position of Sgr A*, and fully compatible with the position reported from the 2004 data set (Aharonian et al. 2006d). Changing the background subtraction technique, the image binning, or the fit boundaries did not affect the position by more than 2''. Assuming a Gaussian distribution of surface brightness, a rms source size upper limit of 1.3 (95% CL) is derived. The fraction of diffuse emission in a circle of 0.1° radius centred on the best-fit position is 14%, consistent with previous findings (Aharonian et al. 2006d, 2009). Fig. 2 shows longitude and latitude slices of the $\gamma$-ray excess map, with the best-fit function overlaid, to demonstrate the performance of the fit.

V. DISCUSSION

Fig. 2 shows a VLA 90 cm image of the innermost 20 pc region of the GC, centred on Sgr A*. The shell-like radio structure of the SNR Sgr A East is clearly visible. The best-fit position of HESS J1745-290 lies in a region where the radio emission is comparatively low, and is shown as a 68% CL total error contour, computed from the summed (in quadrature) statistical and systematic best-fit position errors. As can be seen from the figure, the centroid of the VHE source is coincident with the positions of Sgr A* and G359.95-0.04, but inconsistent with the regions of intense radio emission from Sgr A East. Two rather independent approaches to derive a quantitative
The white stars marked tension and the 68% containment region of the H.E.S.S. PSF, lines show the 95% CL upper limit contour of the source exclusion (Aharonian et al. 2006b). The white and black dashed-dotted contour for the previously reported H.E.S.S. measurement the white circle. The dashed white circle shows the same position was derived by fitting the radio map – smoothed with the H.E.S.S. PSF – with the technique used above for the VHE γ-ray data. Following the methods used for position A, the radio fit position is 5.4 standard deviations away from the best-fit VHE centroid position.

The above results are obtained assuming that the VHE emission and radio morphology are correlated. Since the best-fit position does not coincide with a region of intense radio emission (see Fig. 2), relaxing this assumption leads to more conservative estimates of the association probability. A priori, it would appear conservative to assume that the centroid of TeV emission associated with Sgr A East might appear anywhere within the boundaries, with equal probability. With this assumption one can calculate the probability that the VHE emission is produced inside Sgr A East, but is only by chance positionally coincident with Sgr A* and G359.95-0.04, which themselves are plausible emitters of VHE radiation and thus viable counterpart candidates of HESS J1745-290. Defining the 2 Jy/beam radio contour of Sgr A East as the SNR boundary, which encloses the best-fit position of the emission centroid, a chance probability of $9 \times 10^{-5}$ is derived (corresponding to 3.9 standard deviations). This number does slightly change depending on the assumed size of the SNR boundary. It is clear, however, that even with this conservative approach an association of Sgr A East with the observed VHE γ-ray emission is rather unlikely.

The exclusion of Sgr A East as the main contributor to the VHE emission is a major step towards an identification of HESS J1745-290. Despite the fact that HESS J1745-290 is a non-variable γ-ray source, both G359.95-0.04 and Sgr A* are compelling counterpart candidates, as models exist (see section I), which can explain a steady γ-ray flux and variable X-ray emission from Sgr A* at the same time. More information is needed to discriminate between these two objects. Due to their enhanced angular resolution and sensitivity, and their extended energy range, proposed future VHE γ-ray observatories such as CTA or AGIS could shed light on the open question of which of these sources dominates the production of the VHE γ-ray emission from the gravitational centre of our galaxy.

Acknowledgements

The support of the Namibian authorities and of the University of Namibia in facilitating the construction and operation of H.E.S.S. is gratefully acknowledged, as is the support by the German Ministry for Education and Research (BMBF), the Max Planck Society, the French Ministry for Research, the CNRS-IN2P3 and the Astroparticle Interdisciplinary Programme of the CNRS, the U.K. Science and Technology Facilities Council (STFC), the IPNP of the Charles University, the Polish Ministry of Science and Higher Education, the South African Department of Science and Technology and National Research Foundation, and by the University of Namibia.
We appreciate the excellent work of the technical support staff in Berlin, Durham, Hamburg, Heidelberg, Palaiseau, Paris, Saclay, and in Namibia in the construction and operation of the equipment.

Aharonian F., et al. (H.E.S.S. Collaboration), 2004, Astron. Astrophys., 425, L13
Aharonian F., et al. (H.E.S.S. Collaboration), 2006a, Astron. Astrophys., 457, 899
Aharonian F., et al. (H.E.S.S. Collaboration), 2006b, Phys. Rev. Lett., 97, 221102
Aharonian F., et al. (H.E.S.S. Collaboration), 2006c, Nature, 439, 695
Aharonian F., et al. (H.E.S.S. Collaboration), 2008, Astron. Astrophys., 492, L25
Aharonian F., et al. (H.E.S.S. Collaboration), 2009, Astron. Astrophys., 503, 817
Aharonian F., Neronov A., 2005a, Astrophys. J., 619, 306
Aharonian F., Neronov A., 2005b, Astrophys. Space Science, 300, 255
Albert J., et al., 2006, Astrophys. J., 638, L101
Atoyan A., Dermer C. D., 2004, Astrophys. J., 617, L123
Baganoff F. K., et al., 2001, Nature, 413, 45
Balick B., Brown R., 1974, Astrophys. J., 194, 265
Berger D., Funk S., Hinton J., 2007, Astron. Astrophys., 466, 1219
Braun I., 2007, PhD thesis, University of Heidelberg
Crocker R. M., et al., 2005, Astrophys. J., 622, 892
ESA 1997, ESA SP-1200
Genzel R., et al., 2003, Nature, 425, 934
Gillessen S., 2004, PhD thesis, University of Heidelberg
Gillessen S., et al., 2009, Astrophys. J., 692, 1075
Green D. A., 2009, ArXiv e-prints 0905.3699
Helder E. A., et al., 2009, Science, 325, 719
Hillas A., 1985, Proc. 19th ICRC (La Jolla), 3, 445
Hinton J. A., Aharonian F. A., 2007, Astrophys. J., 657, 302
Hofmann W., et al., 1999, Astropart. Phys., 122, 135
Kosack K., et al., 2004, Astrophys. J., 608, L97
LaRosa T., et al., 2000, Astron. J., 119, 207
Liu S., et al., 2006, Astrophys. J., 647, 1099
Meyer L., et al., 2008, Astrophys. J., 688, L17
Porquet D., et al., 2003, Astron. Astrophys., 407, L17
Reid M., et al., 1999, Astrophys. J., 524, 816
Rowell G. P., 2003, Astron. Astrophys., 410, 389
Tsuboi M., Handa T., Ukita N., 1999, Astrophys. J. Suppl., 120, 1
Tsuchiya K., et al., 2004, Astrophys. J., 606, L115
Wang Q. D., Lu F. J., Gotthelf E., 2006, Mon. Not. Roy. Astron. Soc., 367, 937
Wang Y.-P., Lu Y., Chen L., 2009, Res. Astron. Astrophys., 9, 761
Yusef-Zadeh F., et al., 1996, Astrophys. J., 466, L25