DISCOVERY OF VERY HIGH ENERGY γ-RAY EMISSION FROM CENTAURUS A WITH H.E.S.S.

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ABSTRACT

We report the discovery of faint very high energy (VHE; $E > 100$ GeV) γ-ray emission from the radio galaxy Centaurus A in observations performed with the High Energy Stereoscopic System (H.E.S.S.) experiment, an imaging atmospheric Cherenkov telescope array consisting of four telescopes located in Namibia. Centaurus A has been observed for more than 120 hr. A signal with a statistical significance of 5.0σ is detected from the region including the radio core and the inner kpc jets. The integral flux above an energy threshold of $\sim$250 GeV is measured to be 0.8% of the flux of the Crab Nebula (apparent luminosity: $L(>250$ GeV$) \approx 2.6 \times 10^{39}$ erg s^{-1},

adopting a distance of 3.8 Mpc). The spectrum can be described by a power law with a photon index of $2.7 \pm 0.5_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}$. No significant flux variability is detected in the data set. However, the low flux only allows detection of variability on the timescale of days to flux increments above a factor of $\sim$15–20 (3σ and 4σ, respectively). The discovery of VHE γ-ray emission from Centaurus A reveals particle acceleration in the source to >TeV energies and, together with M 87, establishes radio galaxies as a class of VHE emitters.

Key words: galaxies: active – galaxies: individual (Cen A) – gamma rays: observations

1. INTRODUCTION

Centaurus A (Cen A) is the nearest active galaxy (for a review see Israel 1998). It is classified as an FR I radio galaxy; these are thought to be the parent population of BL Lac objects (Urry & Padovani 1995). At radio wavelengths rich jet structures are visible, extending from the core and the inner pc and kpc jet to giant outer lobes with an angular extension of $8° \times 4°$. The inner kpc jet has also been detected in X-rays, revealing a complex structure of bright knots and diffuse emission (Kraft et al. 2002). The angle of the jet axis to the line of sight is estimated to be $15°$–$80°$ (see, e.g., Horiuchi et al. 2006, and references therein). With a distance of 3.8 Mpc (Rejkuba 2004; $1'$ corresponds to $\sim$1.1 kpc projected length) even the inner jet structures are resolvable with the angular resolution of current experiments in the very high energy (VHE; $E > 100$ GeV) regime.[34] The elliptical host NGC 5128 features a dark lane, a thin edge-on disk of dust and young stars, believed to be the remnant of a merger. Recent estimates for the mass of the central supermassive black hole give $(5.5 \pm 3.0) \times 10^7$ $M_\odot$ (Cappellari et al. 2008). The kpc-scale jet and the active nucleus are confirmed sources of strong nonthermal emission. In addition, more than 200 X-ray point sources with an integrated luminosity of $L_X > 10^{38}$ erg s^{-1} are established to be associated with the host galaxy (Kraft et al. 2001). Recently, Croston et al. (2009) reported the detection of nonthermal X-ray emission from the shock of the southwest inner radio lobe from deep *Chandra* observations.

Cen A was detected at MeV to GeV energies by all instruments on board the Compton Gamma-Ray Observatory (CGRO) in the period 1991–1995, revealing a peak in the spectral energy distribution (SED) in νF_ν representation at $\sim$0.1 MeV with a maximum flux of about $\sim$10^{-9} erg cm^{-2} s^{-1} (Steinle et al. 1998). Steinle et al. (1998) also reported the variability of the Cen A source, especially pronounced at 10 MeV, while Sreekumar et al. (1999) found the EGRET flux was stable during the whole period of CGRO observations. A tentative detection of Cen A (4.5σ) at VHE during a giant X-ray outburst in the 1970s was reported by Grindlay et al. (1975). Subsequent VHE observations made with the Mark III (Carramiñana et al. 1990), JANZOS (Allen et al. 1993), CANGAROO (Rowell et al. 1999; Kabuki et al. 2007), and High Energy Stereoscopic System (H.E.S.S.; Aharonian et al. 2005) experiments resulted in upper limits.

Cen A has been proposed as a possible source of ultra-high energy cosmic rays (UHECR; $E > 6 \times 10^{19}$–10^{20} eV; Romero et al. 1996, but see also Lemoine 2008). Recently, the Pierre Auger Collaboration reported an anisotropy in the arrival direction of UHECR (Abraham et al. 2007, 2008). While a possible correlation with nearby active galactic nuclei (AGNs) is still under discussion, it has been pointed out that several of the events can possibly be associated with Cen A (e.g., Gorbunov et al. 2008; Moskalenko et al. 2008; Kachelriess et al. 2008).

Until now, the only firmly established extragalactic VHE γ-ray source with only weakly beamed emission is the giant radio galaxy M 87 (Aharonian et al. 2003, 2006a). M 87 showed strong flux outbursts in the VHE regime with timescales on the order of days (Aharonian et al. 2006a; Albert et al. 2008), pointing to a characteristic size of the emission region less than $5 \times 10^{15}\delta$ cm, corresponding to $\approx$5δ Schwarzschild radii ($M_{\mathrm{BH}} = 3.2 \times 10^9$ $M_\odot$, δ: relativistic Doppler factor). Recently, Aliu et al. (2009) and Acciari et al. (2009) reported VHE emission from the direction of the blazar 3C 66 A and the radio galaxy 3C 66 B (angular separation $6'$). While Aliu et al. (2009) favor 3C 66 B as the origin of the VHE emission in their data set, Acciari et al. (2009) exclude 3C 66 B as the origin of their detected emission with a significance of 4.3σ.

In this Letter, the discovery of VHE emission from Cen A with the H.E.S.S. experiment is reported, and properties of the detected emission and their implications are discussed.

2. H.E.S.S. OBSERVATIONS AND RESULTS

The H.E.S.S. Collaboration operates an array of four large imaging Cherenkov telescopes (IACT) for the detection of VHE γ-rays, located in the Southern Hemisphere in Namibia (Aharonian et al. 2006b). The H.E.S.S. observations of Cen A were performed between 2004 April and 2008 July. A dead time corrected total live time of 115.0 hr of good-quality data was recorded. The zenith angles of the observations range from $20°$ to $60°$ with a mean zenith angle of $\sim$24°. The data were recorded with pointing offsets between $0°.5$ and $0°.7$ relative to the radio core position, to enable a simultaneous estimation of the background using events from the same field of view (reflected background) (Aharonian et al. 2006b). The data were analyzed with a standard Hillas-type analysis (Aharonian et al. 2006b) with an analysis energy threshold of $\sim$250 GeV for a zenith angle of $20°$.
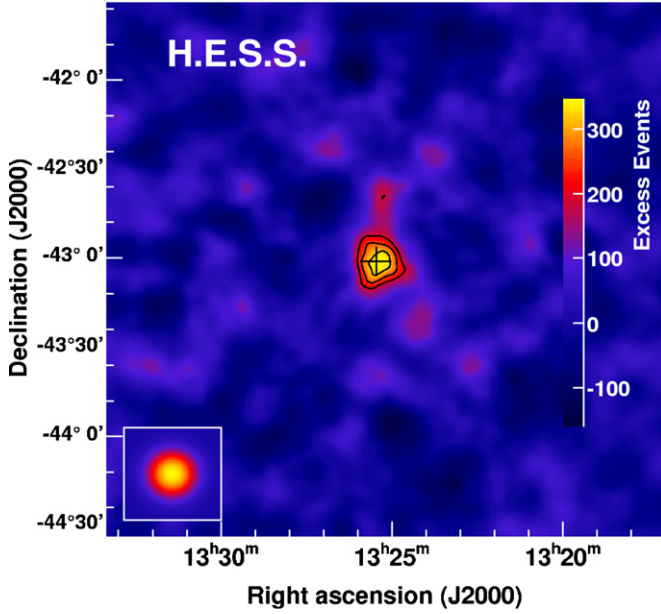
Figure 1 shows the smoothed excess sky map of VHE γ-rays as measured with H.E.S.S. centered on the Cen A radio core position. A clear excess at the position of Cen A is visible. A point-source analysis, using standard cuts as described in Aharonian et al. (2006b), was performed on the radio core position of Cen A, resulting in the detection of an excess with a statistical significance of 5.0σ (calculated following Equation (17) of Li & Ma 1983; 330 excess events, $N_{\mathrm{ON}} = 4199$, $N_{\mathrm{OFF}} = 42513$, $\alpha = 0.091$). A fit of the instrumental point-spread function (PSF)[35] to the uncorrelated sky map results in a good fit (chance probability $\sim$0.7) with a best fit position of $\alpha_{J2000} = 13^{\mathrm{h}}25^{\mathrm{m}}26.4^{\mathrm{s}} \pm 4.6^{\mathrm{s}}_{\mathrm{stat}} \pm 2.0^{\mathrm{s}}_{\mathrm{syst}}$, $\delta_{J2000} = -43°0'.7 \pm 1'.1_{\mathrm{stat}} \pm 30''_{\mathrm{syst}}$, well compatible with the radio core and the inner kpc jet region (Figure 2). Assuming a Gaussian surface brightness profile, we derive an upper limit of $0°.2$ on the extension (95% confidence level).

[34] H.E.S.S. angular resolution: $\sim$6$'$ per event, $\sim$6–30$''$ systematic error on position depending on the data set (van Eldik et al. 2008).

[35] Derived from Monte Carlo simulations.

Figure 1. Smoothed excess sky map centered on the Cen A radio core (cross). Overlaid contours correspond to statistical significances of 3, 4, and 5σ, respectively. The inlay in the lower left corner shows the excess expected from a point source (derived from Monte Carlo simulations). The integration radius is $0°.1225$ and the map has been smoothed with a two-dimensional Gaussian of radius $0°.02$ to reduce the effect of statistical fluctuations. The cosmic-ray background in each bin is estimated using the template background method (Rowell 2003).
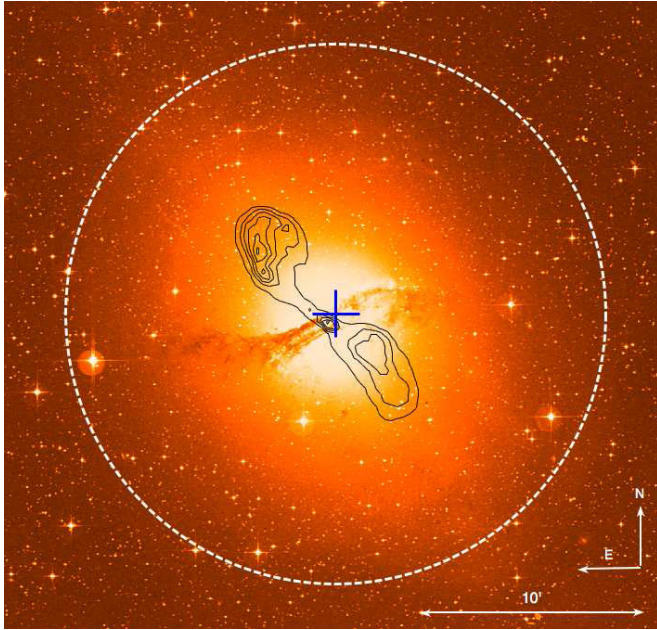
Figure 2. Optical image of Cen A (UK 48 inch Schmidt) overlaid with radio contours (black, VLA, Condon et al. 1996), VHE best fit position with 1σ statistical errors (blue cross), and VHE extension upper limit (white dashed circle, 95% confidence level).

The differential photon spectrum of the source is shown in Figure 3.[36] A fit of a power-law function $dN/dE = \Phi_0 \cdot (E/1\,\text{TeV})^{-\Gamma}$ to the data is a statistically good description ($\chi^2/\text{dof} = 2.76/4$) with normalization $\Phi_0 = (2.45 \pm 0.52_{\text{stat}} \pm$

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[36] To derive the energy spectrum, a looser cut on the distance to the source is used ($\theta^2 < 0.03\,\text{deg}^2$) to increase the number of photons (the standard cut is $\theta^2 < 0.015\,\text{deg}^2$).
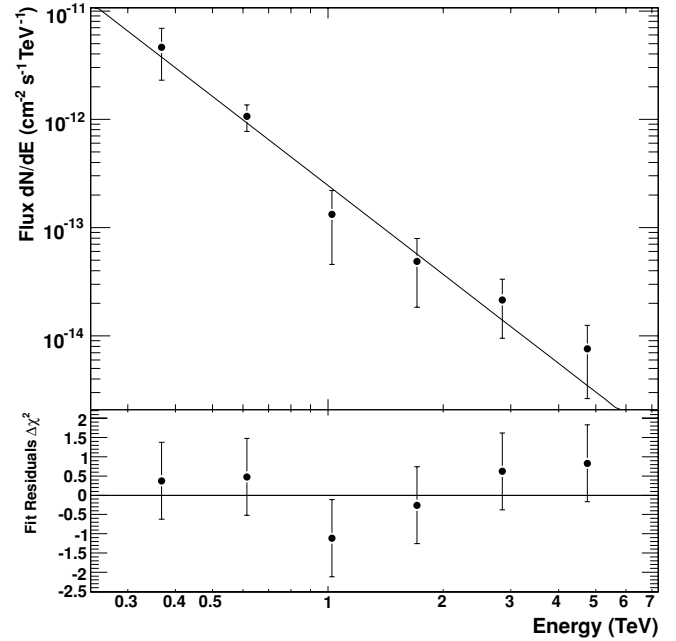
Figure 3. Differential energy spectrum of Cen A as measured by H.E.S.S. The line is the best fit of a power law $dN/dE = \Phi_0 \cdot E^{-\Gamma}$ to the data ($\Gamma = 2.7 \pm 0.5_{\text{stat}} \pm 0.2_{\text{sys}}$). The lower panel shows the residual $\Delta\chi^2$ of the fit.

$0.49_{\text{sys}}) \times 10^{-13}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{TeV}^{-1}$ and photon index $\Gamma = 2.73 \pm 0.45_{\text{stat}} \pm 0.2_{\text{sys}}$. The integral flux above 250 GeV, taken from the spectral fit, is $\Phi(E > 250\,\text{GeV}) = (1.56 \pm 0.67_{\text{stat}}) \times 10^{-12}\ \text{cm}^{-2}\ \text{s}^{-1}$, which corresponds to $\sim 0.8\%$ of the flux of the Crab Nebula above the same threshold (Aharonian et al. 2006b), or an apparent luminosity of $L(> 250\,\text{GeV}) = 2.6 \times 10^{39}\ \text{erg}\,\text{s}^{-1}$ (adopting a distance of 3.8 Mpc).

No significant variability has been found on timescales of 28 minutes, nights and months (moon periods). From the error on the nightly flux ($\sim 5\%$ crab), we estimate the sensitivity of the data set for flares with a duration of 1 day. For an $\sim 4\sigma$ detection in the Cen A data set a flux increase during a single night by a factor of ≈ 20 would be needed (a factor of ≈ 15 for $\sim 3\sigma$). This can be compared to the VHE flux variation of factor ~ 5–10 detected from M 87 on timescales of days.

The results have been cross-checked with independent analysis and calibration chains and good agreement was found.

3. DISCUSSION

Figure 4 shows the SED of Cen A ranging from X-rays to the VHE regime. The flux measured by H.E.S.S. is clearly below all previous upper limits in the VHE regime. Extrapolating the spectrum measured with EGRET in the GeV regime to VHE energies roughly matches the H.E.S.S. spectrum, though the softer end of the error range on the EGRET spectral index is preferred. The recently launched Fermi observatory should provide a more accurate spectrum in the MeV–GeV range soon.

Several authors have predicted VHE emission from Cen A, and more generally discussed VHE emission from radio galaxies. A first class of models proposed the immediate vicinity of the supermassive black hole as the region of VHE emission. Neronov & Aharonian (2007) and Rieger & Aharonian (2008) proposed a pulsar-type particle acceleration in the magnetosphere of the sub-Eddington accreting supermassive black hole, which has been applied successfully to the low-luminosity radio galaxy M 87. In this model, the relation $L_{\text{IC}} \propto M_{\text{BH}}$ is expected
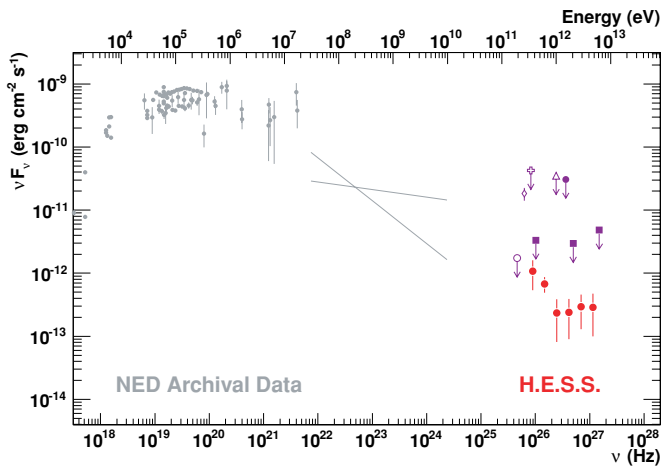
Figure 4. SED of Cen A. Shown are the VHE spectrum as measured by H.E.S.S. (red filled circles), previous upper limits and tentative detections in the VHE regime (purple markers; Grindlay et al. 1975: open diamond; Carramiñana et al. 1990: open cross; Allen et al. 1993: filled circle; Rowell et al. 1999: open triangle; Aharonian et al. 2005: open circle; Kabuki et al. 2007: filled squares), EGRET measurements in the GeV regime (Sreekumar et al. 1999: gray bow tie), and data from the NASA Extragalactic Database (NED; gray filled circles).

(see Equation (12) in Rieger & Aharonian 2008). Since the mass of the central black hole and the VHE luminosity from Cen A are ~10 times lower than those in M 87, such a model could possibly be applied to the current data on Cen A.

It has also been proposed that, similar to the mechanism at work in other VHE blazars, VHE emission could be produced in the inner jet regions in radio galaxies (Bai & Lee 2001; Chiaberge et al. 2001). Given the jet angle of 15°–80° toward the observer (see, e.g., Horiuchi et al. 2006, and references therein), the relativistic boosting in standard scenarios would be small. Ghisellini et al. (2005) proposed a two-flow type model (Sol et al. 1989), with a fast spine and a slower, mildly relativistic sheath propagating within the jet, which has been successfully applied to M 87 (Tavecchio & Ghisellini 2008). Their model for the SED of Cen A (see Figure 3 in Ghisellini et al. 2005), which was mainly constrained by the available CGRO data, cuts off at lower frequencies than VHE, but could possibly account for H.E.S.S. data by refining the parameters (see also in this context Marcowith et al. 1998). Lenain et al. (2008) modeled the VHE emission of Cen A with a multiblob synchrotron self-Compton (SSC) model. In this model, VHE emission is expected to take place in the broadened jet formation zone, where even for a large jet angle, a few emission zones can move directly toward the observer and Doppler boost the emission. Their model prediction for the VHE emission from Cen A is well compatible with the H.E.S.S. data reported here (see Figure 7 in Lenain et al. 2008).

More extended VHE emission may also be expected from Cen A. In this context, Stawarz et al. (2006) proposed that γ-rays emitted in the immediate vicinity of the active nucleus are partly absorbed by the starlight radiation in the host galaxy. The created $e^{\pm}$ pairs are quickly isotropized and radiate VHE γ-rays by inverse Compton scattering the starlight radiation. The small size of the resulting isotropic pair halo (~4 arcmin in diameter) is fully consistent with a pointlike source for H.E.S.S., but could be resolved by the future Cherenkov Telescope Array (CTA)[37] observatory. Stawarz et al.'s prediction for the VHE emission of Cen A within this model, resulting in a steady flux

of a few 10^{-13} erg cm^{-2} s^{-1} and a photon index of ~2.6 at the TeV energy range, agrees well with the H.E.S.S. spectrum (see Figure 6 in Stawarz et al. 2006).

Furthermore, hadronic models have been invoked to predict VHE emission from radio galaxies. In this context, Reimer et al. (2004) proposed a synchrotron-proton blazar model for M 87 where the high-energy component in the SED is interpreted in terms of synchrotron emission from either primary protons or secondary $\mu^{\pm}$ and $\pi^{\pm}$ created in the inner jet. At larger distances and in the peculiar case of Cen A, ultrarelativistic protons with $E_p < 10^{18}$ eV could be released within the kpc-scale jet, and would be then confined in the host galaxy by interactions with the interstellar magnetic field. Both the dust lane of Cen A and thermal gas of the merger remnant could act as efficient, dense targets of cold material for these protons, resulting in VHE γ-ray emission.

Kachelriess et al. (2008) considered possible UHECR emission from Cen A in the view of the CGRO observations and current limits provided by imaging atmospheric Cherenkov telescopes. Depending on the choice for the UHECR injection function in their model, some solutions proposed for the predicted VHE γ-ray spectrum are compatible with the H.E.S.S. results reported here (see Figure 1 in Kachelriess et al. 2008).

It has also been argued that VHE emission could originate from the outer giant radio lobes (e.g., Hardcastle et al. 2008) lying at ~4° from the core. However, the VHE γ-ray excess presented here only matches the position of the core, the pc/kpc inner jets and the inner radio lobes. Only upper limits at VHE have been derived for the southern outer lobe (Kabuki et al. 2007).

Recently, Croston et al. (2009) reported the detection of nonthermal X-ray synchrotron emission from the shock of the southwest inner radio lobe. The edge of this lobe is located ~5′ from the nucleus and reveals edge-brightened X-ray emission (Kraft et al. 2003). While the position is ~3σ away from the best fit position of the VHE excess, it is well within the upper limit of the extension. Studying the spatial variation of the spectral index in X-rays across this shock region, Croston et al. (2009) constrained the high energy cutoff in the electron distribution to be $\gamma_{\max} \sim 10^8$. They investigated inverse Compton scattering the starlight radiation and the CMB from high-energy particles in this lobe and predicted a VHE emission well compatible with the H.E.S.S. measurement reported here (see their Figure 8) for both seed radiation fields. This study would suggest that Cen A is analogous to a gigantic supernova remnant (SNR).

Besides the components of the AGNs hosted in Cen A, one might wonder whether other sources in the host galaxy could be responsible for the VHE emission. For example, Kraft et al. (2001) detected more than 200 X-ray point sources in Cen A, and IACTs have detected about 60 VHE sources in our Galaxy, many of which are associated with SNRs and pulsar wind nebulae (PWNe). However, source ensembles, such as the sum of the contributions from SNRs/PWNe, would require an unrealistically large number of sources (assuming a typical luminosity of ~10^{34}–10^{35} erg s^{-1} above 250 GeV per source).

Further information on the VHE excess position, more detailed spectral shape, and variability studies are required to differentiate between the different models. However, if the VHE emission is due to a misaligned blazarlike process—such as leptonic or hadronic emission from the jet—the proximity of Cen A makes it a very good laboratory to further investigate emission processes and jet physics in blazars. If the VHE emission originates from another process—e.g., UHECR interacting with the

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[37] http://www.cta-observatory.org/.

interstellar medium, or an SNR-type process at the shock—this would be very exciting, giving new insights into the physics in the VHE domain.

Cen A represents a rich potential for future VHE experiments. Our current data are at the edge of differentiating the possible emitting regions. With higher sensitivity (a factor of 10), better astrometric accuracy, and angular resolution (e.g., $\sim5''$ and $\sim1'$, respectively) (Hermann et al. 2007), CTA would allow the localization of the site of the VHE emission, and, possibly, reveal multiple VHE emitting sources within Cen A. More generally, the detection of VHE emission from Cen A together with the detection of M 87 and the galactic center poses the question of whether VHE emission (γ-ray brightness) might be a general feature of AGNs. While the sensitivity of current generation experiments is probably too low to answer this question, one can hope that the CTA experiment will be able to detect a large enough sample of sources to shed some light on this issue.

REFERENCES

Abraham, J., et al. (Pierre Auger Collaboration) 2007, Science, 318, 938
Abraham, J., et al. (Pierre Auger Collaboration) 2008, Astropart. Phys., 29, 188
Acciari, V. A., et al. (VERITAS Collaboration) 2009, ApJ, 693, L104
Aharonian, F., et al. (HEGRA Collaboration) 2003, A&A, 403, L1
Aharonian, F., et al. (H.E.S.S. Collaboration) 2005, A&A, 441, 465
Aharonian, F., et al. (H.E.S.S. Collaboration) 2006a, Science, 314, 1424
Aharonian, F., et al. (H.E.S.S. Collaboration) 2006b, A&A, 457, 899
Albert, J., et al. (MAGIC Collaboration) 2008, ApJ, 685, L23
Aliu, E., et al. (MAGIC Collaboration) 2009, ApJ, 692, L29
Allen, W. H., et al. (JANZOS Collaboration) 1993, ApJ, 405, 554
Bai, J. M., & Lee, M. G. 2001, ApJ, 549, L173
Cappellari, M., Neumayer, N., Reunanen, J., van der Werf, P. P., de Zeeuw, P. T., & Rix, H. 2008, MNRAS, at press (arXiv:0812.1000)
Carramiñana, A., et al. 1990, A&A, 228, 327
Chiaberge, M., Capetti, A., & Celotti, A. 2001, MNRAS, 324, L33
Condon, J. J., Helou, G., Sanders, D. B., & Soifer, B. T. 1996, ApJS, 103, 81
Croston, J. H., et al. 2009, arXiv:0901.1346
Ghisellini, G., Tavecchio, F., & Chiaberge, M. 2005, A&A, 432, 401
Gorbunov, D., Tinyakov, P., Tkachev, I., & Troitsky, S. 2008, Sov. J. Exp. Theor. Phys. Lett., 87, 461
Grindlay, J. E., Helmken, H. F., Brown, R. H., Davis, J., & Allen, L. R. 1975, ApJ, 197, L9
Hardcastle, M. J., Cheung, C. C., Feain, I. J., & Stawarz, L. 2008, MNRAS, 393, 1041
Hermann, G., Hofmann, W., Schweizer, T., & Teshima, M. (for the CTA Consortium) 2007, 30th Int. Cosmic Ray Conf., ed. R. Caballero, Vol. 3, 1313
Horiuchi, S., Meier, D. L., Preston, R. A., & Tingay, S. J. 2006, PASJ, 58, 211
Israel, F. P. 1998, A&AR, 8, 237
Kabuki, S., et al. (CANGAROO III Collaboration) 2007, ApJ, 668, 968
Kachelriess, M., Ostapchenko, S., & Tomas, R. 2008, arXiv:0805.2608
Kraft, R. P., Forman, W. R., Jones, C., Murray, S. S., Hardcastle, M. J., & Worrall, D. M. 2002, ApJ, 569, 54
Kraft, R. P., Kregenow, J. M., Forman, W. R., Jones, C., & Murray, S. S. 2001, ApJ, 560, 675
Kraft, R. P., Vázquez, S. E., Forman, W. R., Jones, C., Murray, S. S., Hardcastle, M. J., Worrall, D. M., & Churazov, E. 2003, ApJ, 592, 129
Lemoine, M. 2008, in in SF2A-2008, ed. C. Charbonnel, F. Combes, & R. Samadi, 247
Lenain, J.-P., Boisson, C., Sol, H., & Katarzyński, K. 2008, A&A, 478, 111
Li, T. P., & Ma, Y. Q. 1983, ApJ, 272, 317
Marcowith, A., Henri, G., & Renaud, N. 1998, A&A, 331, L57
Moskalenko, I. V., Stawarz, L., Porter, T. A., & Cheung, C. C. 2008, arXiv:0805.1260
Neronov, A., & Aharonian, F. A. 2007, ApJ, 671, 85
Reimer, A., Protheroe, R. J., & Donea, A.-C. 2004, A&A, 419, 89
Rejkuba, M. 2004, A&A, 413, 903
Rieger, F. M., & Aharonian, F. A. 2008, A&A, 479, L5
Romero, G. E., Combi, J. A., Perez Bergliaffa, S. E., & Anchordoqui, L. A. 1996, Astropart. Phys., 5, 279
Rowell, G. P. 2003, A&A, 410, 389
Rowell, G. P., et al. (CANGAROO Collaboration) 1999, Astropart. Phys., 11, 217
Sol, H., Pelletier, G., & Asseo, E. 1989, MNRAS, 237, 411
Sreekumar, P., Bertsch, D. L., Hartman, R. C., Nolan, P. L., & Thompson, D. J. 1999, Astropart. Phys., 11, 221
Stawarz, Ł., Aharonian, F., Wagner, S., & Ostrowski, M. 2006, MNRAS, 371, 1705
Steinle, H., et al. 1998, A&A, 330, 97
Tavecchio, F., & Ghisellini, G. 2008, MNRAS, 385, L98
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
van Eldik, C., Bolz, O., Braun, I., Hermann, G., Hinton, J., & Hofmann, W. 2008, J. Phys. Conf. Ser., 110, 062003