# Discovery of VHE $\gamma$-ray emission from Centaurus A with H.E.S.S.

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***Abstract*. Up to now, all extragalactic sources of very high energy (VHE; $E > 100\,\mathrm{GeV}$) $\gamma$-rays are active galactic nuclei. Almost all of them belong to the class of blazars, which are active galactic nuclei with the jet axis closely aligned to the line of sight and the emission relativistically boosted. One exception is the radio galaxy M 87: in radio galaxies the plasma jets are inclined with a larger angle to the line of sight, enabling spatial studies of the jet structure in many wavelength bands. Here, we present the discovery of VHE $\gamma$-ray emission from the nearest radio galaxy Centaurus A with H.E.S.S. The detection of Centaurus A confirms radio galaxies as a new source class of VHE $\gamma$-rays. The implications of these results on the emission site and on the different models available will be discussed.**

***Keywords*: $\gamma$-rays: observations, Galaxies: individual: Centaurus A, Radiation mechanisms: non-thermal**

## I. Introduction

Centaurus A (Cen A) is the nearest active radio galaxy (3.8 Mpc [1]; for a review see [2]) and has been very well studied at all wavelengths. In the radio band, rich jet structures are visible, extending from the core and the inner pc and kpc jet to giant outer lobes that span a region of $8^\circ \times 4^\circ$. The inner kpc jets have also been detected in X-rays, revealing bright knots, diffuse emission and a counter-jet (see [3], [4]). The kpc-scale jet and the active nucleus are confirmed sources of strong non-thermal radiation. In addition, more than 200 X-ray point sources with an integral luminosity of $L_X > 10^{38}\,\mathrm{erg\,s^{-1}}$ are established to be associated with the host galaxy [5].

The viewing angle between the jet axis and the line of sight is estimated to be 15°–80° (see e.g. [6] and references therein). The elliptic host NGC 5128 features a dark lane, famous to amateur astronomers, made of a disk of dust and young stars viewed edge-on, which is believed to be the remnant of a merger. Recent indirect measurements of the mass of the central supermassive black hole give $(5.5 \pm 3.0) \times 10^7 M_\odot$ [7].

Cen A was detected from MeV to GeV energies with all instruments onboard the Compton Gamma-Ray Observatory (*CGRO*) between 1991 and 1995. These observations revealed a peak in the spectral energy distribution (SED) in $\nu F_\nu$ representation at $\sim$0.1 MeV with a maximum flux of $\sim 10^{-9}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ [8]. Very recently, the *Fermi*/LAT collaboration reported the detection of Cen A at GeV energies [9]. In the 1970's, [10] reported an early tentative detection of Cen A at the $4.5\sigma$ level during a giant X-ray outburst. Subsequent observations with different VHE instruments resulted in upper limits. Cen A has also been proposed as a source of ultra-high energy cosmic rays by [11], but see also [12].

Until now, the only firmly established extragalactic VHE $\gamma$-ray source with only weakly beamed emission was the giant radio galaxy M 87 (see [13], [14]) lying at $\sim$16 Mpc. M 87 showed strong flux outbursts in the VHE regime with time scales of the order of days (see [14], [15]), pointing to a characteristic size of the emission region less than $2.6 \times 10^{15} \delta\,\mathrm{cm}$, $\delta$ being the relativistic Doppler factor. Recently, the MAGIC and VERITAS collaborations reported VHE emission from the direction of the blazar 3C 66A ($z = 0.444$, but uncertain) and the FR I radio galaxy 3C 66B ($z = 0.0215$), spatially separed by $6'$ (see [16] and [17] respectively). While the MAGIC collaboration favors 3C 66B as the origin of the VHE emission in their data set, the VERITAS collaboration excludes this radio galaxy as the orgin of their detected emission with a significance of $4.3\sigma$.

## II. H.E.S.S. observations and results

The H.E.S.S. (High Energy Stereoscopic System) collaboration operates an array of four large imaging atmospheric Čerenkov telescopes for the detection of VHE $\gamma$-rays, located in the Southern Hemisphere in Namibia [18].

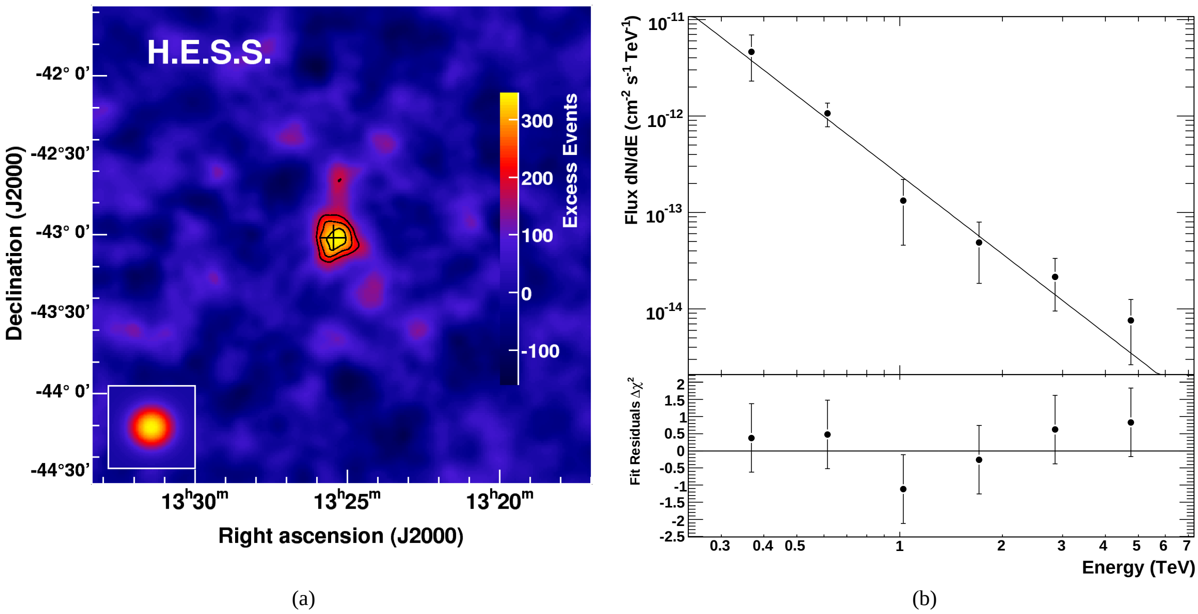


Fig. 1. (*a*): Smoothed excess sky map of VHE $\gamma$-rays centered on the Cen A radio core (cross) (contours: 3, 4, and 5$\sigma$). (*b*): Differential energy spectrum of Cen A at VHE as measured by H.E.S.S.

Cen A was observed using the H.E.S.S. experiment between April 2004 and July 2008, yielding a dead time corrected total live time of 115.0 h, with zenith angles ranging from 20° to 60° with a mean zenith angle of $\sim$24°. The data were analyzed with a standard Hillas-type analysis [18] with an analysis energy threshold of $\sim$250 GeV for a zenith angle of 20°.

Figure 1a shows the smoothed excess sky map of VHE $\gamma$-rays 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 [18], yields to the detection of an excess of VHE $\gamma$ rays with a statistical significance of $5.0\sigma$. A fit of the instrumental point spread function to the uncorrelated sky map results in a good fit (chance probability$\sim$0.7) with a best fit position of $\alpha_{\rm J2000} = 13^{\rm h}25^{\rm m}26.4^{\rm s} \pm 4.6^{\rm s}_{\rm stat} \pm 2.0^{\rm s}_{\rm syst}$, $\delta_{\rm J2000} = -43°0.7' \pm 1.1'_{\rm stat} \pm 30''_{\rm syst}$, well compatible with the radio core and the inner kpc jet regions. We derive an upper limit of 0.2° on the extension (95% confidence level), assuming a Gaussian surface-brightness profile.

The differential photon spectrum, shown in Fig. 1b, is well described by a power law function $dN/dE = \Phi_0(E/1\,{\rm TeV})^{-\Gamma}$ with a normalization $\Phi_0 = (2.45 \pm 0.52_{\rm stat} \pm 0.49_{\rm syst}) \times 10^{-13}\,{\rm cm}^{-2}\,{\rm s}^{-1}\,{\rm TeV}^{-1}$ and a photon index $\Gamma = 2.73 \pm 0.45_{\rm stat} \pm 0.20_{\rm syst}$. Calculated from the spectral fit, the integral flux above 250 GeV is $\Phi(E > 250\,{\rm GeV}) = (1.56 \pm 0.67_{\rm stat}) \times 10^{-12}$ ${\rm cm}^{-2}\,{\rm s}^{-1}$, corresponding to $\sim$0.8% of the flux of the Crab Nebula above the same threshold [18], and to an apparent isotropic[1] luminosity of $L(E > 250\,{\rm GeV}) \approx 2.6 \times 10^{39}\,{\rm erg\,s}^{-1}$ (adopting a distance of 3.8 Mpc).

[1]not corrected for a potential Doppler boosting effect.

No significant variability has been found on time scales of 28 min, nights and months (moon periods). However, given the faint flux, only large flares–such as a brightening by a factor $\approx$20 over a night for a $\sim 4\sigma$ detection of a flaring event–would have been detectable. This can be compared to the VHE flux variation of factor $\sim$5–10 detected from M 87 on time scales of days.

The results have been cross-checked with independent analysis and calibration chains, and good agreement was found. More details can be found in [19].

## III. Discussion

Figure 2 shows the SED of Cen A from X-rays to the VHE range. The flux measured by H.E.S.S. is clearly below all previous upper limits reported in the VHE regime. Recently, the *Fermi*/LAT collaboration reported the detection of Cen A at GeV energies [9] (see Fig. 2, orange bow-tie). Assuming a simple power law extrapolation to the VHE range would result in a flux too low at $\sim$TeV energies, however one should await for the release of the actual spectral points from *Fermi* before concluding about the compatibility of the H.E.S.S. and *Fermi* data. Moreover, one could argue that these data are not contemporaneous and that variability could possibly account for some of the difference.

Several authors have predicted VHE emission from Cen A or similar sources. A first class of models proposed the immediate vicinity of the central supermassive black hole as the VHE emitter, as in e.g. pulsar-type scenarios (see [20], [21]). A second class of models invokes a similar mechanism to the one at work in other TeV blazars (see [22], [23]). In a two-flow framework [25], Marcowith *et al.* [26] reproduces the high energy emission of Cen A modeling a relativistic pair beam

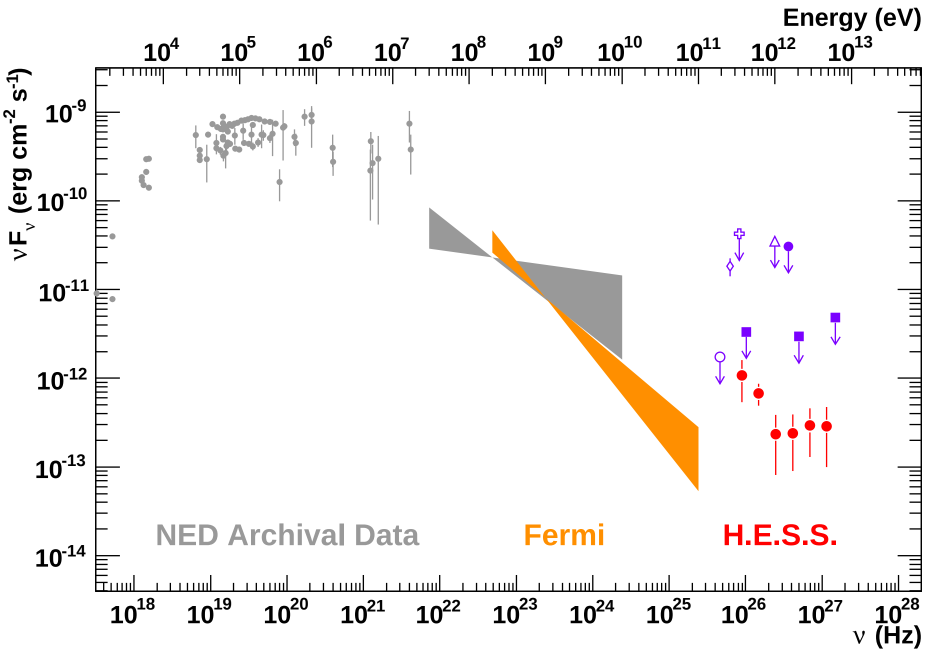


Fig. 2. High energy part of the spectral energy distribution of Cen A. The bow-tie in orange represents the recent measurement with *Fermi*/LAT. In the VHE domain, the H.E.S.S. spectrum is shown in red while previous upper limits are in blue. In gray are shown the measurements obtained with the different instruments onboard *CGRO*.

scattering soft photons coming from an accretion disk. In the same two-flow spirit, [24] proposed a model applied to the previous results from *CGRO* for Cen A, with a fast moving spine and a slower, mildly relativistic sheath, which has also been successfully applied to M 87 [27]. [28] also successfully modeled the VHE emission from M 87 with another two-flow type scenario, for which several blobs radiate through synchrotron self-Compton process in the broadened formation zone of the jet, and proposed a prediction for the VHE emission from Cen A which is in good agreement with the current data.

More extended VHE emission is also expected from Cen A. Indeed, [29] proposed that $\gamma$-rays emitted in the immediate vicinity of the active galactic nucleus (AGN) are partly absorbed by the starlight radiation in the host galaxy. The created $e^{\pm}$ pairs are quickly isotropized and radiate VHE $\gamma$-rays by inverse Compton scattering off the starlight radiation. Furthermore, hadronic models have also been invoked to predict VHE emission from radio galaxies (in this context, see e.g. [30]). The H.E.S.S. results do not yet strongly constrain these models.

Recently, [31] reported the detection of non-thermal X-ray synchrotron emission from the southwest inner radio lobe. From the X-rays emission properties of this region, they constrained the high energy cutoff in the electron energy distribution to be $\gamma_{\rm max}{\sim}10^8$. They investigated inverse Compton scattering of starlight and CMB radiation by high energy particles in this region and predicted a VHE emission well compatible with the H.E.S.S. results. This study suggests that Cen A could be analogous to a gigantic supernova remnant. Even though the position is $\sim3\sigma$ away from the H.E.S.S. best fit position, it is still well compatible with the upper limit of 0.2° on the extension.

Further information on the VHE excess position, more detailed spectral shape, and potential variability studies would enable differentiation between the different emission models. However, if VHE emission is due to a misaligned blazar-like process–such as leptonic or hadronic emission from the jet–the proximity of Cen A would make it a very good laboratory to further investigate these classical emission processes and jet physics in blazars. If VHE emission originates from another process–e.g. ultra high energy cosmic rays interacting with the interstellar medium, or an SNR-type process at a shock as suggested by recent *Chandra* results [31]–this would give new insights into the physics in the VHE domain and in the context of multi-messenger studies.

Cen A represents a rich potential for future VHE experiments. The current data are just at the edge of differentiating the possible emitting regions. With higher sensitivity (factor 10), better astrometric accuracy and angular resolution (e.g. $\sim5''$ and $\sim1'$ respectively, [32]), the CTA (Čerenkov Telescope Array)[2] observatory would allow the precise localization of the site of the VHE emission, and, possibly, reveal multiple VHE emitting sources within Cen A. More generally, the detection of VHE $\gamma$-ray emission from Cen A, together with the detection of M 87, poses the question of whether such emission might be a common 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

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

large enough sample of sources to shed some light on this issue.

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