Mem. S.A.It. Vol. 81, 362

Memorie della

TeV Active Galactic Nuclei: multifrequency modeling

J.-P. Lenain

LUTH, Observatoire de Paris, CNRS, Université Denis Diderot; 5 Place Jules Janssen, 92190 Meudon, France. e-mail: jean-philippe.lenain@obspm.fr

Abstract. In the recent years, the new generation of Imaging Atmospheric Čerenkov Telescopes successfully detected very high energy (VHE; $E > 100\,\mathrm{GeV}$) γ-ray emission from a growing number of Active Galactic Nuclei (AGNs), mainly belonging to the blazar class.
Among these recent results, we will mainly focus in this work on two recent discoveries made with the H.E.S.S. experiment: the tremendously active state of the blazar PKS 2155−304 observed in July 2006 and the discovery of VHE γ-rays from the radio galaxy Cen A. On the one hand, the observation of very fast variability in PKS 2155−304 challenges the current radiative standard models for TeV blazars. On the other hand, the discovery of Cen A as a source of VHE γ-rays firmly establishes, together with the previous detection of M 87, radio galaxies as a new class of VHE emitters.

Key words. Galaxies: active – Galaxies: BL Lacertae objects: individual: PKS 2155−304 – Galaxies: individual: Cen A – Gamma-rays: observations – Gamma-rays: theory – Radiation mechanisms: non-thermal

1. Introduction

With the advent of the current generation of Imaging Atmospheric Čerenkov Telescopes (IACTs) such as H.E.S.S.[1], MAGIC[2], VERITAS[3] and CANGAROO[4], our vision of the sky at very high energy (VHE; $E > 100\,\mathrm{GeV}$) has dramatically changed. In less than ten years, the number of sources detected at VHE has increased from 5 to more than seventy as of writing this manuscript[5].

The majority of them belongs to our Galaxy, while about 25 extragalactic sources have been reported, all of them being active galactic nuclei (AGNs) and most of these being of the blazar class. Blazars are compounded by flat spectrum radio quasars and BL Lac, the jet of which is closely aligned to the line of sight, thus amplifying the observed flux by relativistic Doppler boosting. These objects present a double bump-shaped spectral energy distribution (SED), the first

Send offprint requests to: J.-P. Lenain

[1] http://www.mpi-hd.mpg.de/hfm/HESS/

[2] http://wwwmagic.mppmu.mpg.de/

[3] http://veritas.sao.arizona.edu/

[4] http://icrhp9.icrr.u-tokyo.ac.jp/

[5] see e.g. the TeVCat catalog online at http://tevcat.uchicago.edu/ for an up-to-date list of known VHE sources.

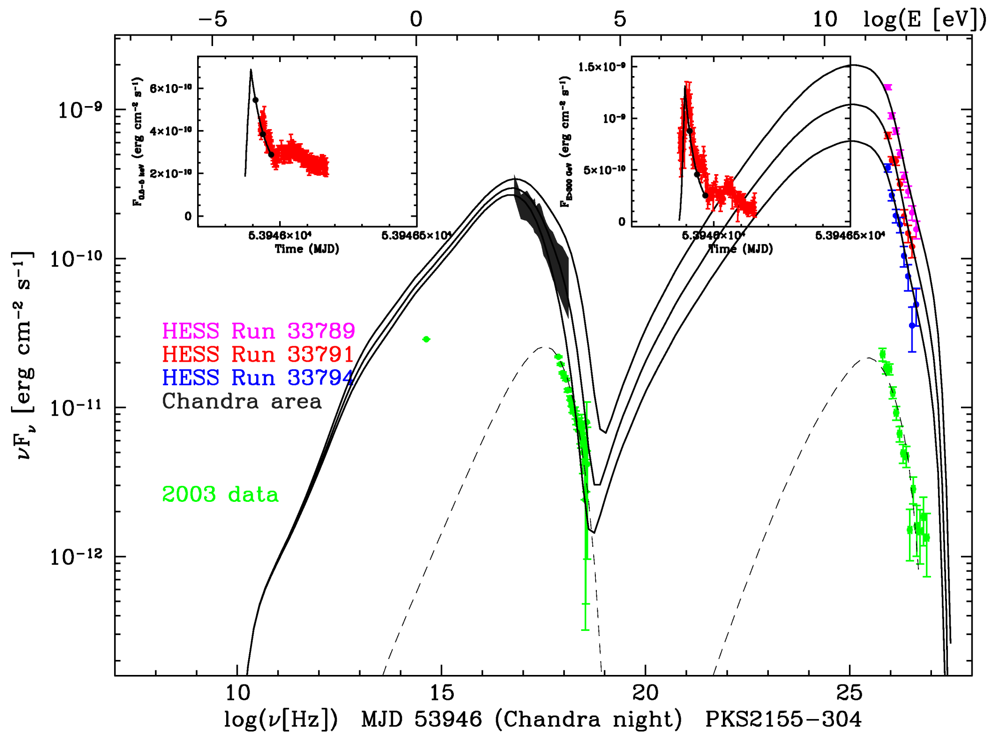

Fig. 1. Spectral energy distribution obtained with the dynamic SSC modeling of the second flare of PKS 2155−304 observed in July 2006 with H.E.S.S. Each solid line corresponds to a snapshot of the evolving SED, simultaneous to the three derived H.E.S.S. spectra during the night. The inlays show the corresponding X-ray (*left*) and VHE (*right*) light curves, the three spectra represented in the SED corresponding to the three epochs marked in black dots in the light curves.

bump – peaking in the optical/X-ray domain – being generally attributed to leptonic synchrotron emission, while the nature of the second bump – peaking in the GeV domain – is more unclear. In leptonic models, it could be attributed to synchrotron self-Compton (SSC, e.g. Maraschi et al. 1992) or external inverse Compton (e.g. Sikora et al. 1994) processes.

Hadronic emission could also be responsible for this high energy bump, through the radiation of secondary particles created by proton interaction on protons (e.g. Orellana & Romero 2009), photons (e.g. Mannheim et al. 1991; Mücke et al. 2003) or magnetic fields (Aharonian 2002), even though these models can usually hardly interpret fast variability compared to leptonic models, as for example in the case of the fast VHE flux variability observed from 1ES 1959+650 in 2002 (Krawczynski et al. 2004), Mrk 501 in 2005 (Albert et al. 2007), and from PKS 2155−304 in 2006 (Aharonian et al. 2007; Lenain et al. 2008a).

2. The multi-blob SSC model

In a leptonic framework, we developed a multi-blob SSC model (Lenain et al. 2008b) to interpret the VHE data taken by H.E.S.S. on the radio galaxy M 87 (Aharonian et al. 2006). In this model, an inhomogeneous flow continuously crossing a stationary shock front, located in the innermost part of the broadened jet formation region beyond the Alfvén surface as inferred from magnetohydrodynamics models (e.g. McKinney 2006), could lead to a differential Doppler boosting effect that could lead to a significant blazar-like effect even for sources with a misaligned jet (see Lenain et al. 2008b, for more details).

Using this model, we interpreted the VHE spectrum measured by H.E.S.S. in 2004 from M 87, and predicted possible detectable VHE emission from other misaligned blazar-like sources like Cen A, 3C 273 or PKS 0521−36. Particularly, we predicted a detectable flux from Cen A with current IACTs at a $\sim 5\sigma$ confidence level in ~50 h of observations.

3. The blazar PKS 2155−304

PKS 2155−304 is a blazar known to emit VHE γ-rays since the early days of VHE γ-ray astronomy (Chadwick et al. 1999). In 2003, the H.E.S.S. collaboration reported a low activity state which could be interpreted in both leptonic and hadronic frameworks (Aharonian et al. 2005). However, in July 2006, PKS 2155−304 showed to be in a very active state, and experienced two dramatic flaring events on July 28 (Aharonian et al. 2007) and July 30, 2006 (Lenain et al. 2008a), the second burst exceeding a peak flux of 16 Crab. Moreover, simultaneous X-ray coverage with *Chandra* revealed a nearly cubic relationship between the X-ray flux and the VHE flux, ruling out one-zone SSC models for the interpretation of this event.

Using a dynamic SSC model (Katarzyński et al. 2003), we were able to interpret this rich data set with a two-zone SSC model, in which the synchrotron component of a slowly evolving, extended jet dominates the X-ray radiation, while a small, dense blob dominates the inverse Compton component and is responsible for the fast variability in VHE (see Fig. 1, and also Lenain et al. 2008a). By increasing the density ratio between the extended jet and the blob, we obtained a template solution for an orphan VHE flare event (see Fig. 2), similar to the one observed in 1ES 1959+650 in 2002 (in this context see also Katarzyński et al. (2008) for a similar interpretation of the first flare of July 28, 2006).

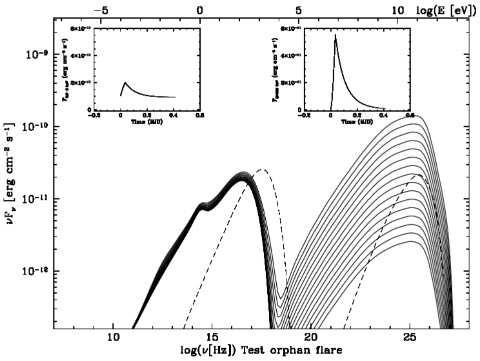

Fig. 2. Dynamic spectral energy distribution for a template solution of an orphan VHE flare event, like the one observed in 1ES 1959+650 in 2002 (Krawczynski et al. 2004). The inlays represent the X-ray (*left*) and VHE (*right*) light curves. The overall event lasts for ~10 h. For comparison, the low state of activity of PKS 2155−304 as observed with H.E.S.S. in 2003 is represented in dashed lines.

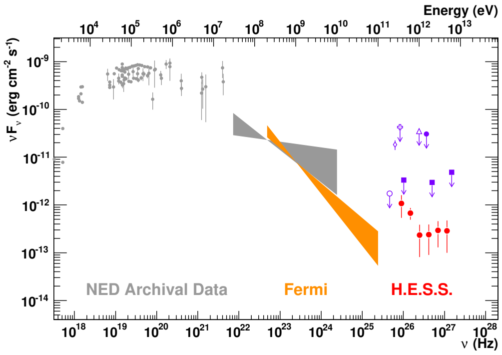

Fig. 3. High energy part of the spectral energy distribution of Cen A, with archival data from *CGRO*, the recent *Fermi*/LAT (Abdo 2009) and H.E.S.S. (Aharonian et al. 2009) spectra.

4. The radio galaxy Cen A

Cen A is the nearest radio galaxy, of the FR-I type, at a distance of 3.8 Mpc. The H.E.S.S. collaboration carried out observations on this object between April 2004 and June 2008, more than 60% of the data being taken in 2008. After more than 100 h of observations, Cen A was eventually detected in the VHE domain as a point-like source at the 5σ confidence level, and the corresponding apparent luminosity was derived to be $L(E > 250\,\mathrm{GeV}) \approx 2.6 \times 10^{39}\,\mathrm{erg\,s^{-1}}$ (see Fig. 3, and Aharonian et al. 2009, for more details). This discovery, together with the previous detection of M 87, firmly establishes radio galaxies as a new class of VHE emitters.

Given the poor spatial resolution in the VHE domain compared to other wavelengths, many different interpretations are consistent with the detection of VHE γ-rays from Cen A, however the giant radio lobes can be excluded as the VHE emitting zone. For example, Cen A could be seen as a misaligned blazar (see e.g. Ghisellini et al. 2005; Lenain et al. 2008b). Hadronic models could also possibly account for these data (see e.g. Reimer et al. 2004, for an application to M 87). VHE emission could arise from extended structures, by external inverse Compton on the starlight radiation (Stawarz et al. 2006), or in analogy with a supernova remnant-type process at a large scale as suggested by the recent results of Croston et al. (2009) conducted with *Chandra* and revealing efficient leptonic acceleration in the inner south-western radio lobe. It has also been argued that the immediate vicinity of the central supermassive black hole could be a VHE emitting zone (see Neronov & Aharonian 2007; Rieger & Aharonian 2008, for an application to M 87).

Superimposing the recent H.E.S.S. spectrum to our early prediction for the VHE flux of Cen A obtained with the multi-blob SSC model (see Fig. 4), even though being only one of the many possible interpretations, one can see that our prediction agrees quite well with the recent VHE data.

5. Conclusions

In conclusion, the detected VHE AGNs present a very heterogeneous broadband behavior and sometimes extreme flaring activities, especially in the case of blazars. The discovery of VHE γ-rays from one of the nearest AGN, Cen A, clearly establishes radio galaxies as a new class of VHE emitting sources.

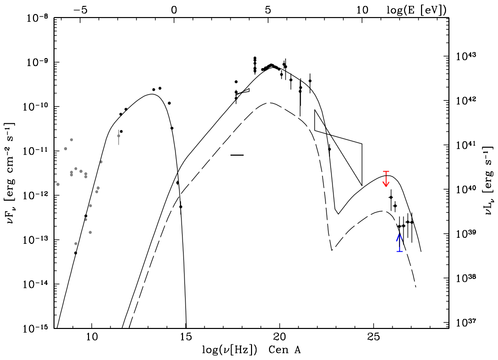

Fig. 4. SED of Cen A assuming that the soft γ-ray emission detected by *CGRO* is of synchrotron nature within the multi-blob SSC model, including the recent H.E.S.S. spectrum.

With the fifth telescope of the H.E.S.S. experiment (the H.E.S.S. II project) coming online soon, and with the data from *Fermi*, the peak of the second component in the SEDs of blazars is expected to be detected, which will strongly constrain all the radiative models available for the processes involved in the emission from AGN jets.

With the advent of CTA (Čerenkov Telescope Array[6]) and AGIS (Advanced Gamma-ray Imaging System[7]), many more discoveries are expected, with probably towards a thousand sources to be discovered.

6. DISCUSSION

JAMES H. BEALL: In your multi-blob model, do you imagine them emerging sequentially or in different directions simultaneously ?

JEAN-PHILIPPE LENAIN: It is a stationary model, thus the dynamics of the bulk motion of the blobs is not considered.

Moreover, it should just be seen as an illustrative sketch, as implemented in our code. Physically, one should consider it as representing an inhomogeneous flow continuously

[6] `http://www.cta-observatory.org/`

[7] `http://www.agis-observatory.org/`

crossing a stationary shock front within the jet, just beyond the Alfvén surface.

Acknowledgements. I am very grateful to the organizers of the Frascati Workshop 2009 on "Multifrequency Behaviour of High Energy Cosmic Sources" (Vulcano, Italy) for their invitation to speak, and for creating a very pleasant and stimulating atmosphere for discussions during this workshop.

It is my pleasure to deeply thank my PhD advisors, Dr. Catherine Boisson and Dr. Hélène Sol, and my colleague Dr. Andreas Zech from the LUTH for discussions and support during my PhD study. Finally, my thanks go to all the members of the H.E.S.S. collaboration for their technical support and for many stimulating discussions.

References

Abdo, A. A., et al. (*Fermi*/LAT collaboration) 2009, `arXiv:0902.1559`
Aharonian, F. A., et al. (H.E.S.S. collaboration) 2005, A&A, 442, 895
Aharonian, F. A., et al. (H.E.S.S. collaboration) 2006, Science, 314, 1424
Aharonian, F. A., et al. (H.E.S.S. collaboration) 2007, ApJ, 664, L71
Aharonian, F. A., et al. (H.E.S.S. collaboration) 2009, ApJ, 695, L40
Aharonian, F. A. 2002, MNRAS, 332, 215
Albert, J., et al. (MAGIC collaboration) 2007, ApJ, 669, 862
Chadwick, P. M., et al. 1999, ApJ, 513, 161
Croston, J. H., Kraft, R. P., Hardcastle, M. J., et al. 2009, MNRAS, 395, 1999
Ghisellini, G., Tavecchio, F., & Chiaberge, M. 2005, A&A, 432, 401
Katarzyński, K., Lenain, J.-P., Zech, A., Boisson, C., & Sol, H. 2008, MNRAS, 390, 371
Katarzyński, K., Sol, H., & Kus, A. 2003, A&A, 410, 101
Krawczynski, H., Hughes, S. B., Horan, D., et al. 2004, ApJ, 601, 151
Lenain, J.-P., et al. (for the H.E.S.S. collaboration) 2008a, in American Institute of Physics Conference Series, Vol. 1085, 415–418
Lenain, J.-P., Boisson, C., Sol, H., & Katarzyński, K. 2008b, A&A, 478, 111
Mannheim, K., Biermann, P. L., & Kruells, W. M. 1991, A&A, 251, 723
Maraschi, L., Ghisellini, G., & Celotti, A. 1992, ApJ, 397, L5
McKinney, J. C. 2006, MNRAS, 368, 1561
Mücke, A., Protheroe, R. J., Engel, R., Rachen, J. P., & Stanev, T. 2003, Astroparticle Physics, 18, 593
Neronov, A. & Aharonian, F. A. 2007, ApJ, 671, 85
Orellana, M. & Romero, G. E. 2009, `arXiv:0902.0731`
Reimer, A., Protheroe, R. J., & Donea, A.-C. 2004, A&A, 419, 89
Rieger, F. M. & Aharonian, F. A. 2008, A&A, 479, L5
Sikora, M., Begelman, M. C., & Rees, M. J. 1994, ApJ, 421, 153
Stawarz, Ł., Aharonian, F., Wagner, S., & Ostrowski, M. 2006, MNRAS, 371, 1705