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J. Bouvier, A. Chalabaev, C. Charbonnel (eds)

EXTRAGALACTIC VHE GAMMA-RAY ASTRONOMY IN THE H.E.S.S. ERA

B. Giebels[1]

Abstract. The observational field of extragalactic γ-ray astronomy has dramatically evolved in the past years, with the new generation of Atmospheric Čerenkov Telescopes (ACTs) such as H.E.S.S. and MAGIC coming online, and probing the radiative properties of Active Galactic Nuclei (AGN) with improved levels of sensitivity and spectral resolution. Light curves now show evidence for minute time-scale variability in the very high energy (VHE, $E > 100\,\mathrm{GeV}$) γ-ray regime, and quality spectra of objects up to $z \simeq 0.2$ are measured, allowing unprecedented constraints to the intrinsic behaviour of these objects, or to the Extragalactic Background Light (EBL) they propagate through.

1 The extragalactic VHE skyscape

The contents of Table 1, where all the currently known VHE-emitting blazars are listed, has to be compared with its counterpart written in April 2007 by Krawczynski (2004), which had 6 entries. The new ones are all discoveries from H.E.S.S. and MAGIC, and the experiment to be credited can be identified by the first author's names of the associated journal paper(Aharonian and Albert, respectively). The threefold increase in extragalactic γ-ray emitters, all but one belonging to the BL Lac class, shows how ten-fold improvement in sensitivity translates into increased detections[1].

Source	z	Discovery & Confirmation
Mrk 421	0.031	Punch et al. 1992, Petry et al. 1996
Mrk 501	0.034	Quinn et al.1996, Bradbury et al. 1997
1ES 2344+514	0.044	Catanese et al. 1998, Tluczykont et al.2003
Mrk 180	0.046	Albert et al. 2006
1ES 1959+650	0.047	Nishiyama et al. 1999, Holder et al. 2003, Aharonian et al. 2003
BL Lac	0.069	Albert et al. 2007 arXiv:astro-ph/0703084
PKS 0548-322	0.07	Aharonian et al. 2007, In prep.
PKS 2005-489	0.07	Aharonian et al. 2005
PKS 2155-304	0.117	Chadwick et al. 1999, Hinton et al. 2003
H 1426+428	0.129	Horan et al. 2002, Aharonian et al. 2002, Djannati et al. 2002
ES 0229+200	0.140	Aharonian et al. 2007, In prep
H 2356	0.167	Aharonian et al. 2005
1ES 1218+30.4	0.182	Albert et al. 2006
1ES 1101-232	0.186	Aharonian et al. 2006
ES 0347-121	0.188	Aharonian et al. 2007, In prep.
1ES 1011+496	0.212	Albert et al. 2007 arXiv:0706.4435
PG 1553+113	0.36 (?)	Aharonian et al. 2006, Albert et al. 2006

Table 1. The 17 blazars detected by ACTs as of the date this proceeding was written, ranked by increasing redshift. The references in the table are not given in this paper's reference list for convenience. Note that M87, a detected non-blazar γ-ray source, is not listed here.

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[1] Laboratoire Leprince-Ringuet, Ecole polytechnique, F-91128 Palaiseau

[1] The Galactic sources, far more numerous, are described in this context by G. Lamanna and V. Vitale, see these proceedings

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These objects appearing mostly as point-like objects, the spectacular improvement in spatial γ-ray imaging that H.E.S.S. has achieved is not directly visible, otherwise than through the improved background rejection and hence sensitivity. Note also that the 4 closest objects in Table 1 are all northern hemisphere objects, making them easier targets not only because of their smaller luminosity distance but also because of the smaller attenuation due to their propagation through the EBL.

The propagation effects and the uncertainties thereupon complicate the estimation of what was intrinsically emitted. This is an annoyance for the understanding of the sources. The uncertainty in our understanding of these sources, notably the fact that they can probably not be standard candle-ized, is on the other hand a drawback for the estimations of the EBL imprint on their spectra.

2 Low state emissions

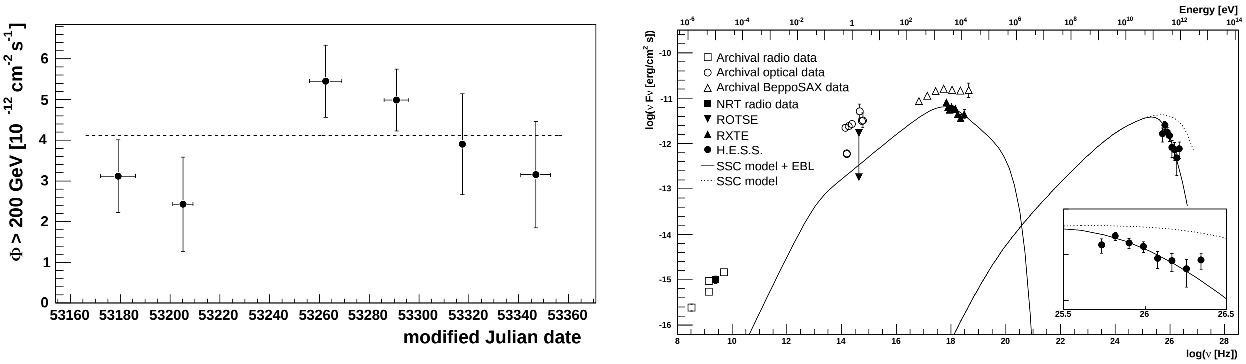

Fig. 1. Left: light curve of H 2356-309 ($z = 0.165$) above 200 GeV in 6 different time windows from June to December 2004. No indication of variability was observed on nightly timescales either. Right: SED of the same object, with contemporaneous data shown as filled symbols. The line is a fit with a single-zone homogenous SSC model. The lack of variability occurs at a time when the source appears to be less intense than archival observations.

The mere detection of a blazar above a given significance level, usually 5 standard deviations (or σ), usually indicated an eruptive episode, because most of the time the source went undetected given the achieved sensitivity. It is now rather striking that detections of blazars often occur when simultaneous observations of their synchrotron component, where for obvious reasons archival data exist to compare with, indicate that the flux levels are close to the lower archival levels. Also, most of the recently discovered blazars with ACTs show relatively flat lightcurves.

The multi-wavelength campaign organized to observe PKS 2155-304 in 2003, thought to be in a high emission state after consecutive nightly detections by H.E.S.S. at the 20% Crab level, showed that the simultaneously measured optical and X-ray levels below those observed in its high state (F. Aharonian et al., 2005) by an order of magnitude. Interestingly, the small level of variability in the different wavelenghts ($\Delta F/F \approx 3$ in both X-rays and γ-rays) was not correlated during these observations, while they were actually seen to be correlated at higher fluxes in the 2004 campaign (B. Giebels et al., 2005). Similar γ-ray detections in low-state synchrotron states were found in the BL Lac object H 2356-309 (Fig.1) with H.E.S.S. (F. Aharonian et al., 2006a), in 1ES 1959+650 (J. Albert et al., 2006) as well as 1ES 1218+30.4 .

3 Variability

The lightcurve of highly eruptive events are often searched for a variability timescale. The high γ-ray statistics allow shorter bins, and Figure 2 shows such an event that happened in July 2006 when the blazar PKS 2155-304 reached unprecedented luminosity levels (W. Benbow, L. Costamante & B. Giebels, 2006), with variability that is among the fastest ever seen for such objects in all wavelenghts.

The fastest resolved transient in the light curve of Fig.2 has a rising timescale of $t_{\rm var} = 173 \pm 28\,$s, which is a factor of 60 to 120 times smaller than the light crossing time of the Schwarzschild radius $R_{\rm S}$ of the $1{-}2{\times}10^9 M_\odot$

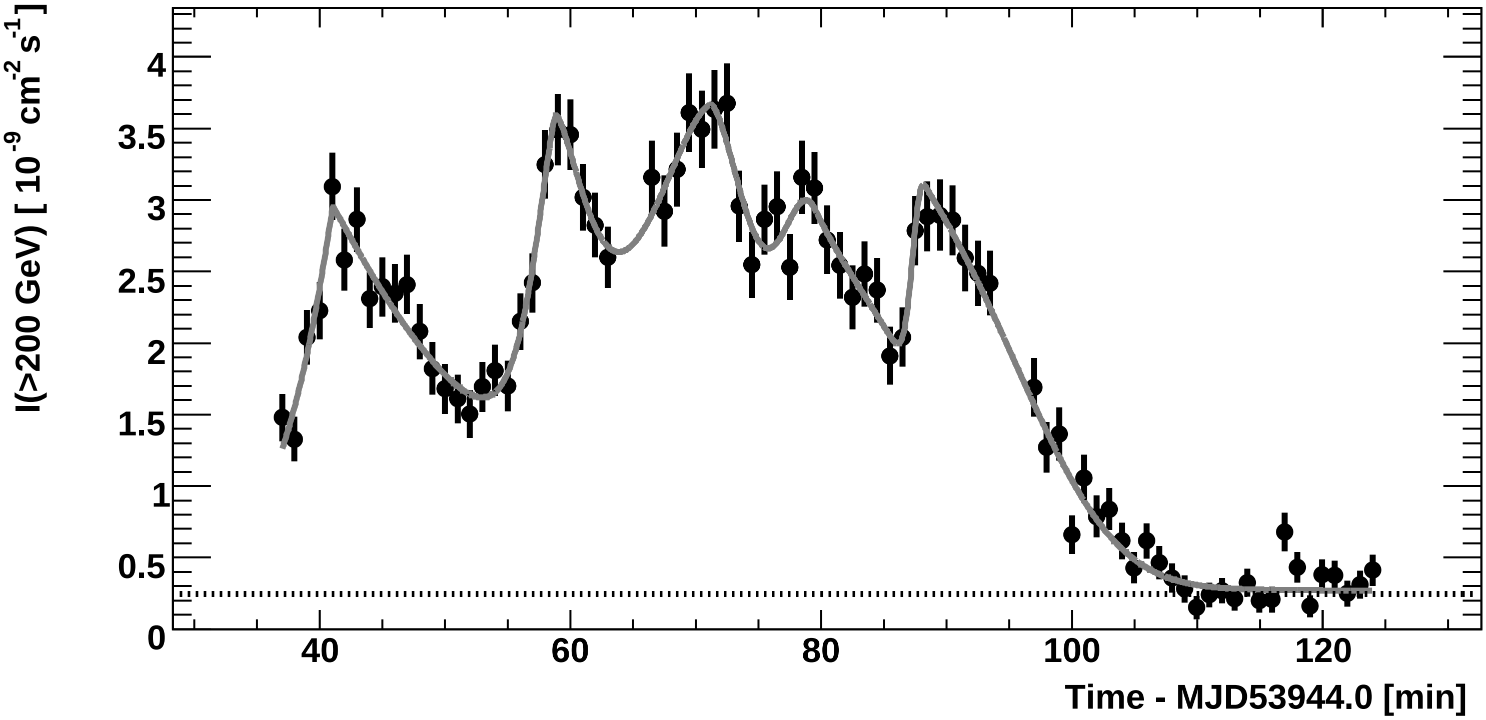

Fig. 2. Light curve of PKS 2155-304 in a high state, on 24 July 2006. The sampling is 1', and the dotted line shows the 1 Crab level.

black hole in the nucleus (F. Aharonian et al., 2007). Doppler boosting of exactly this amount would then allow an emission region radius R of the order of R_{S}, the smallest characteristic size in the system, but at the price of a rather large Lorentz bulk factor this presumes, greater than those typically derived for VHE γ-ray blazars ($\delta \sim 10$) and come close to those used for GRBs, which would be a challenge to understand. Lower values of δ were derived with similar timescales for Mkn 421 (J. Albert et al., 2007), but the remarkable difference for that observation was the rather large spectral variability seen during an outburst, contrary to the outburst of PKS 2155-304.

The power density spectrum (PDS) of this light curve is similar to those derived in X-rays for this object, a featureless power-law Fourier spectrum of index -2 reaching the white noise level at $\sim 1.6 \times 10^{-3}$ Hz (600 s), but with an order of magnitude more power than the archival X-ray PDS at similar frequencies.

4 Propagation effects

During their propagation from the source to the observer, it is well known that γ-rays can interact with ambient intergalactic photons of energy E_p if $E_\gamma E_p \geq 2(m_e c^2)^2$ and create a pair of electrons. An observed spectrum $F(E)$ is then different from the intrinsic F_i spectrum with $F_i(E) = F(E)/\exp -\tau(E)$, $\tau(E)$ being the optical depth. For $100\,\mathrm{GeV} - 10\,\mathrm{TeV}$ photons, the photon field in the $0.1 - 10\,\mu$m is probed and its intensity sets the level of attenuation that affects F_i.

However the shape of F_i is never known, so assumptions have to be largely model-dependent to derive constraints on the EBL. For instance, assuming that the intrinsic photon index Γ_i of $F_i(E)$ cannot be larger than 1.5 in the VHE range, one can readily test some EBL models by constructing the intrinsic spectrum they would predict: the models violating the initial assumption on Γ_i are then seriously in doubt.

Another possibility to derive the spectral energy distribution of the EBL consists in assuming a specific shape for it, and to leave the overall normalization as a free parameter only constrained by the fact that its imprint on the VHE spectrum should not yield a Γ_i smaller than 1.5. Applying this to the object 1ES 1101-232, one of the most distant blazars listed in Table 1, F. Aharonian et al. (2006b) derived limits on the EBL by

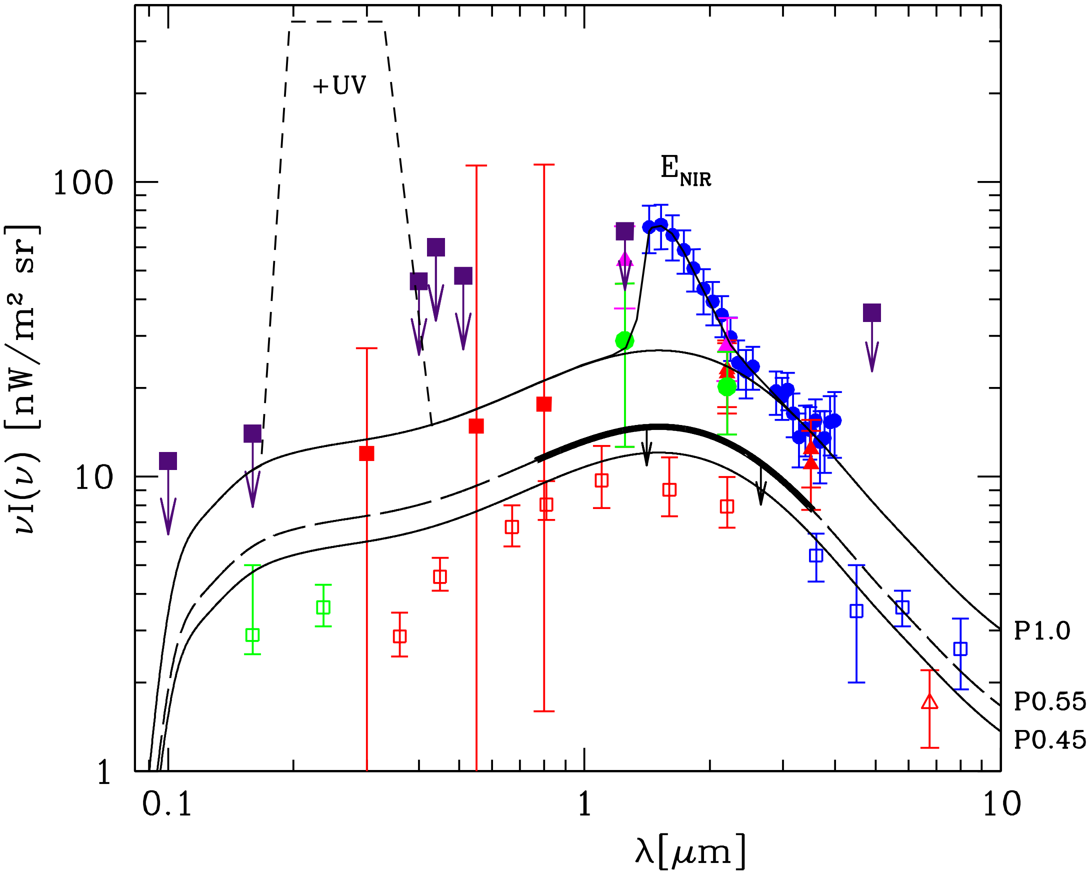

Fig. 3. Spectra energy distribution of the Extragalactic Background Light, in the $0.1 - 10\mu$m band where the H.E.S.S. data are most affected. The curves show the shapes used to constrain the EBL density, with the thick line indicating the range where the data constrain directly the shape. Details are in (F. Aharonian et al., 2006b).

scaling a model designed to be in general agreement with the EBL spectrum expected from galaxy emission (J.R. Primack et al., 2001). Note that the constraint on Γ_i is conservative with respect to the imprint on the VHE spectrum of electromagnetic cascades, initiated by the pair creation, since P. d'Avezac, G. Dubus, & B. Giebels (2007) established that the observed spectrum appears softer than for pure absorption when cascade emission is taken into account.

The rather low EBL level obtained this way is in good agreement with the expectations of standard galaxy evolution models, and is an indication that the Universe is more transparent to γ-rays than initially thought. A similar study on the object 1ES 1218+30.4 (which has also a very flat VHE light curve!), detected by the MAGIC experiment, yielded similar results, showing that the EBL level is remarkably close to the 'incompressible' level derived from resolved source counts.

5 Non-blazars

A result awaiting a decisive confirmation was the detection in VHE γ-rays of the nearby ($z = 0.0008$) radio galaxy M87 by the HEGRA experiment. The large angle of the jet with the line of sight, estimated to be $\theta = 35°$, makes it an unlikely VHE source since Doppler boosting would be too low to make it bright enough. However the marginal detection of Cen A, an object similar to M87 but with $\theta = 60°$, by the EGRET experiment (P. Sreekumar et al., 1999), shows the potential of this nearby unbeamed population of AGN.

Besides confirming M87 as a VHE emitter, variability on daily timescales was detected by H.E.S.S. (Fig.4), which is an order of magnitude faster than the monthly variability set by Chandra measurements in the X-rays. Using the causality argument with a 2-day timescale variability, the size of the γ-ray emitting region is smaller than $5 \times \delta R_{\mathrm{S}}$, excluding the elliptical galaxy itself, the entire extended kiloparsec jet, and dark matter annihilation.

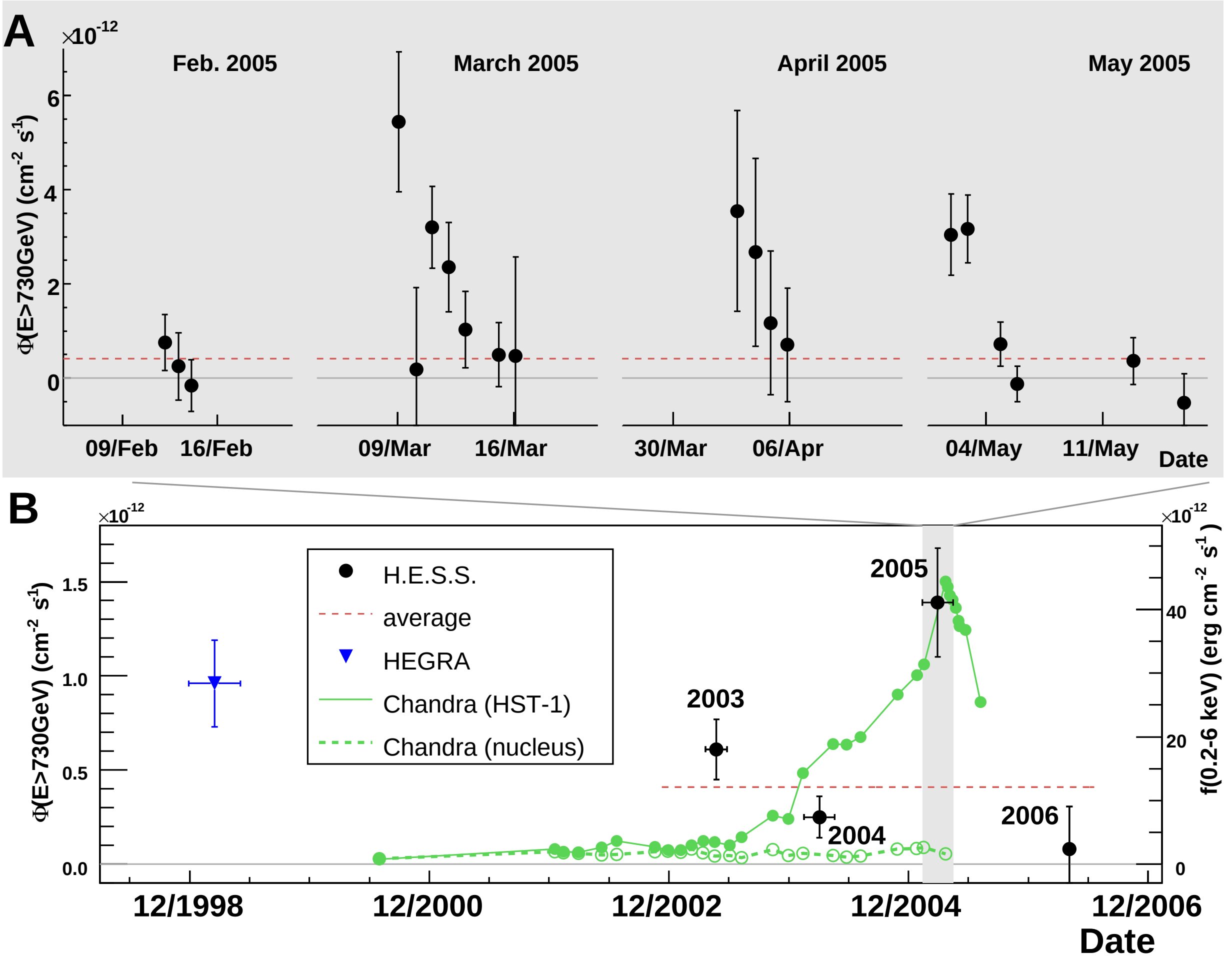

Fig. 4. Light curve above 730 GeV of M87 as measured by H.E.S.S. (F. Aharonian et al., 2006c). The top panel are the nightly fluxes for each observed month of 2005. The yearly fluxes, along with the Chandra measurements of the knot HST-1, are in the bottom plot.

6 Conclusions

So what have we learned in discovering all these new extragalactic sources? A clear global trend as of now is that more and more sources are discovered with little variability in their light curves, which could be interpreted as seeing them in their quiescent level[2]. This is corroborated with the fact that (quasi) contemporaneous observations of the synchrotron component show fluxes that are on the lower bound of archival observations when those are available. Observations of rather low X-ray fluxes are the most convincing fact, since γ-ray variability correlates best with X-rays (even though some ponctual exceptions exist). Having access to quiescent states will give insights on the duty cycle of blazars, as well as rise the question of the relationship with the more variable high flux emission region when these appear.

Individually, spectral measurements of the most distant blazars in VHE γ-rays have considerably constrained the intensity of the EBL in the $0.1 - 10\,\mu$m band, although in a model-dependent way. With little room left for additional components in the EBL, the the steep VHE spectra from relatively nearby objects can be deemed to be due to the intrinsic physical mechanisms at play in the accelerator, rather than EBL attenuation. The search for more distant blazars, with spectra able to constrain event further the EBL SED, doesn't seem over yet.

Very fast variability on minute timescales now leads to an increase in bulk Lorentz factors in the context of homogeneous 1-zone emitting models that are closer to the GRB context. Note that the outburst of PKS 2155-304 shown here is only a fraction of the multi-wavelength campaign that was triggered subsequently, with simultaneous observations in optical and X-ray on the following observations where the flux was also very high. These will be shown and published elsewhere. The monitoring of blazars with the current generation of ACTs could yield other surprises, the radically different spectral behaviour of PKS 2155-304 and Mkn 501 having yet to be understood.

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[2] Higher variability, or variance, has been claimed to be correlated with the flux in X-ray binaries and AGN (P. Uttley, I.M. McHardy, & S. Vaughan, 2005), but this has yet to be established for blazars.