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H.E.S.S. Observations of Extragalactic Jet Sources

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Abstract. The High Energy Stereoscopic System (H.E.S.S.) is the world's largest currently operating Atmospheric Cherenkov Telescope Array. This paper presents highlights of recent results from H.E.S.S. observations of extragalactic jet sources. It will focus on variability studies of the well-known blazars Mrk 501 (discovering minute-scale variability at energies > 2 TeV) and PKS 2155-304, the multiwavelength analysis of the recently discovered blazar PKS 1440-389, and observations of the gravitationally lensed blazar PKS 1830-211, including a brief discussion of the implications of its non-detection by H.E.S.S.

1. Introduction

The High Energy Stereoscopic System (H.E.S.S.) is an array of 5 Cherenkov Telescopes (4×12 m and 1×28 m diameter), located in the Khomas Highland near Windhoek, Namibia, 1800 m above sea level (Aharonian et al. 2006). It observes very-high-energy (VHE: $E > 100$ GeV) γ-rays indirectly by imaging the Cherenkov light from electromagnetic showers produced by VHE γ-rays in the atmosphere. It is operated by an international collaboration of over 200 scientists from 12 countries. The original array of four 12-m telescopes (CT1 – CT4), inaugurated in 2002, constitutes the first phase of operations (H.E.S.S. I, from 2002 - 2012). The addition of the fifth (28-m) telescope (CT5 — which is the largest single Cherenkov telescope in the world) in 2012 ushered in the second phase (H.E.S.S. II), and extended the sensitivity of the array significantly towards lower energies, compared to H.E.S.S. I (see Zaborov et al. 2015 for a more detailed description).

The capabilities of H.E.S.S. II can be exploited in two complementary analysis approaches:

1. CT5 Mono Analysis: CT5 can be used in standalone mode, without consideration of data from CT1 – CT4. This mode yields the lowest possible energy threshold of $E_{\mathrm{thr}} < 100$ GeV.

2. H.E.S.S. II Hybrid Analysis: Considering data from all five telescopes yields the best achievable sensitivity (because of superior background rejection), but at the cost of a slightly higher energy threshold compared to CT5 Mono Analysis.

Figure 1 shows a comparison of the VHE γ-ray spectra of the well-known VHE γ-ray blazar PKS 2155-304, obtained from H.E.S.S. I observations in 2010

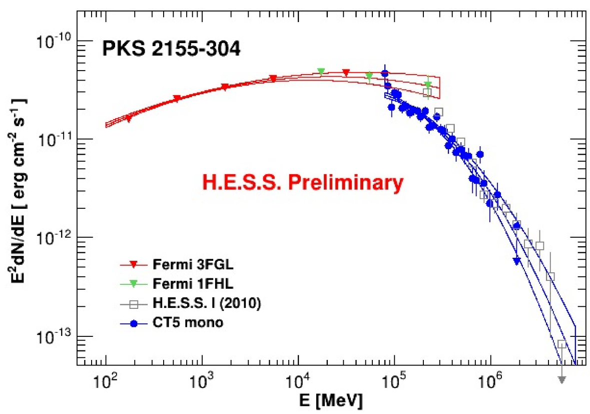

Figure 1. Comparison between H.E.S.S. I and CT5 Mono Analyses, and the *Fermi*-LAT spectrum of the blazar PKS 2155-304. The figure shows excellent agreement between H.E.S.S. I and CT5 as well as significant energy overlap between *Fermi*-LAT and CT5. Reproduced from Zaborov et al. (2015).

(open squares) to CT5 Mono observations (filled circles). It illustrates that (a) there is excellent agreement between H.E.S.S. I and CT5 analyses, and (b) CT5 allows for significant energy overlap with *Fermi*-LAT at $\sim 80 - 300$ GeV. The flux mismatch is a result of the well-known, significant flux variability (e.g., Aharonian et al. 2007), considering the drastically different integration times and non-simultaneity of the *Fermi*-LAT and H.E.S.S. observations.

H.E.S.S. observations of extragalactic targets are focusing on the following key science projects:

1. ToO observations and long-term monitoring of known VHE AGN (primarily blazars, but also radio galaxies, such as Cen A). Science drivers for such observations include diagnostics of particle acceleration, particle content, and the location of the γ-ray emission region in relativistic jets, as well as searches for signatures of physics beyond the standard model (Lorentz Invariance Violation / Axion-Like Particles).
2. Discovery of potential new VHE sources (including radio galaxies, radio-quiet AGN and non-active galaxies). Science drivers include the expansion of the extragalactic VHE source catalogue to enable population studies and probes of the Extragalactic Background Light (EBL), as well as the search for the origin of ultra-high-energy ($E \gtrsim 10^{19}$ eV) cosmic rays (UHECRs).
3. Search for VHE emission from gravitationally lensed blazars (at large redshifts, otherwise likely inaccesible to VHE observations because of severe EBL attenuation).
4. Search for VHE γ-ray emission from gamma-ray bursts (GRBs) — both prompt GRBs and early afterglows.
5. Multimessenger astronomy (including follow-up observations of VHE neutrino events and gravitational-wave triggers).

6. Search for Dark Matter annihilation signatures (in particular, observations of dwarf spheroidal galaxies).

Due to length/time restrictions, this paper will focus on a few recent results and highlights from sub-programs 1. - 3. above. For a recent update on the H.E.S.S. GRB program, see, e.g., Parsons et al. (2015), while more information on the H.E.S.S. multimessenger program can be found in Schüssler et al. (2015), and on the dark matter program in Abramowski et al. (2014a). Recent results of new EBL constraints based on H.E.S.S. observations of blazars can be found in Lorentz et al. (2015).

2. Variability Studies of Known VHE Blazars

There are several well-known VHE γ-ray emitting blazars accessible from the southern hemisphere with sufficiently bright quiescent levels to allow for meaningful long-term monitoring with H.E.S.S. With its 13 years of continuous operations, these on-going H.E.S.S. monitoring observations provide light curves of unprecedented duration and detail for several blazars.

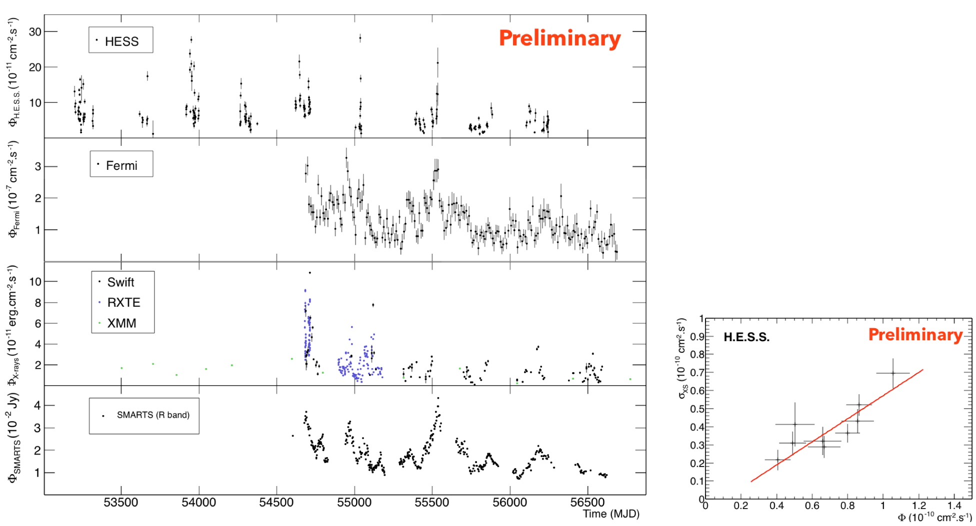

Figure 2. *Left:* The long-term ($\sim$ 12 years) multi-wavelength light curve of PKS 2155-304. *Right:* H.E.S.S. excess variability amplitude as a function of underlying flux level from the long-term light curve of PKS 2155-304. Reproduced from Chevalier et al. (2015).

The prominent high-frequency-peaked BL Lac object (HBL) PKS 2155-304 is a prime example (see, e.g., Abramowski et al. 2014b). Figure 2 (left) shows the H.E.S.S. VHE γ-ray, *Fermi*-LAT HE γ-ray, X-ray, and optical (R-band) light curve of this blazar, indicating the large range of flux states in which H.E.S.S. has detected the source, and the generally close correlation between the variability patterns in these frequency bands, on long time-scales. A study of the excess variability amplitude of the VHE γ-ray variability of PKS 2155-304 as a function of its short-term average flux state (shown in Figure 2, right) reveals a linear correlation, which indicates a multiplicative process driving the γ-ray variability of this blazar.

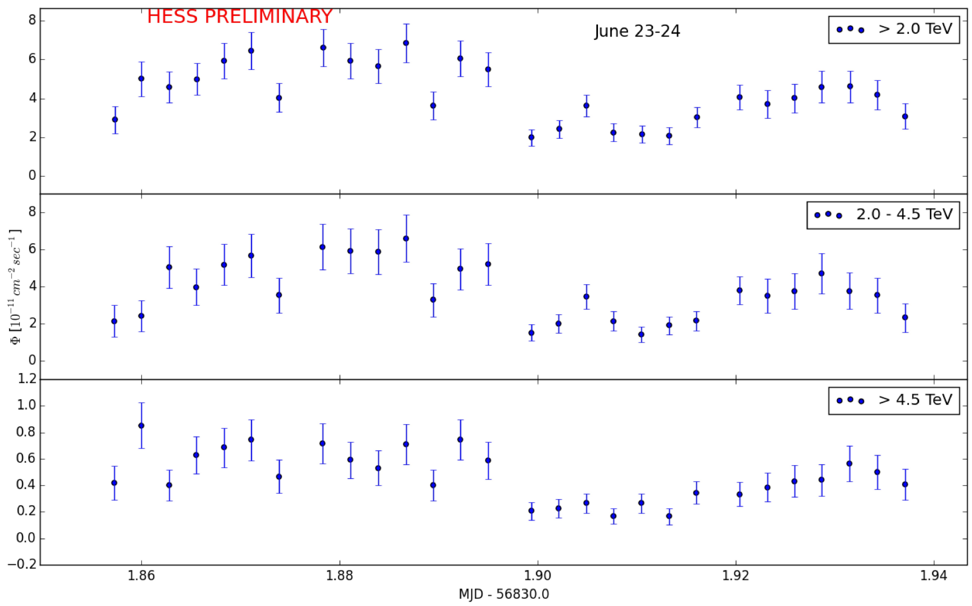

Figure 3. Four-minute binned light curve of the HBL Mrk 501 at $E > 2$ TeV during June 2014, revealing variability on ~ 10 minute time scales. Reproduced from Chakraborty et al. (2015).

Another prominent, VHE-bright blazar which was subject to several coordinated observing campaigns including H.E.S.S. is the HBL Mrk 501. This blazar (as PKS 2155-304) has been known to show very rapid ($\sim$ few minutes) variability in VHE γ-rays, based on low-zenith-angle (and, hence, low-energy threshold, $E \gtrsim 150$ GeV) observations with MAGIC (Albert et al. 2007). In that case, the variability is strongly dominated by the signal of photons near the low-energy threshold, i.e., $E < 1$ TeV. High-zenith-angle observations (with energy threshold $E > 2$ TeV) by H.E.S.S. were performed during major flaring activity of Mrk 501 in June 2014. These led, for the first time, to the detection of rapid ($\lesssim 10$ min.) variability clearly associated with $E > 2$ TeV photons (Fig. 3). This result is particularly interesting as it rules out a cosmic-ray induced origin of the multi-TeV emission, at least in the case of Mrk 501, which has been invoked to explain an apparent deficit in EBL induced $\gamma\gamma$ attenuation for moderate-redshift ($z \lesssim 0.5$) blazars (e.g., Essey et al. 2010).

3. New Discovery: PKS 1440-389

One of the most recent new blazar discoveries by H.E.S.S. is the BL Lac object PKS 1440-389. H.E.S.S. observations were motivated by the hard *Fermi*-LAT spectrum with a photon index of $\Gamma_{\rm LAT} = 1.77 \pm 0.06$. The redshift of this source

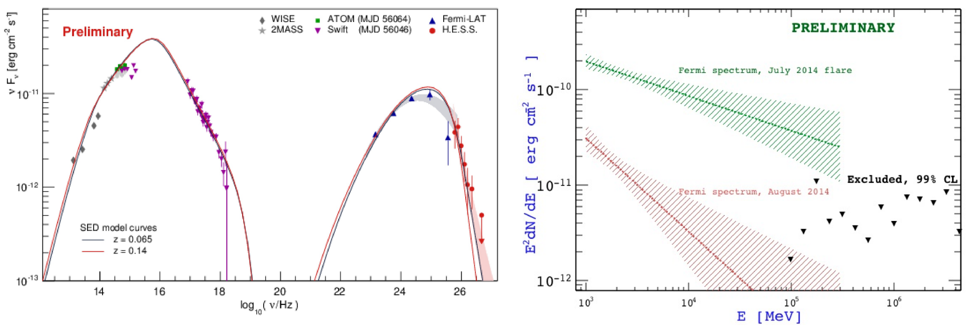

Figure 4. *Left:* Spectral energy distribution of PKS 1440-389, with two single-zone, leptonic SSC fits for redshifts $z = 0.065$ and $z = 0.14$. Reproduced from Prokoph et al. (2015). *Right:* *Fermi*-LAT spectra (quiescent and flaring) of PKS 1830-211, compared to 99 % CL upper limits from H.E.S.S., indicating a significant deficit of VHE emission compared to the flaring-state LAT spectrum. Reproduced from Glicenstein et al. (2015).

is uncertain. While a preliminary redshift of $z = 0.065$ appeared in an early version of the 6dF Galaxy Survey, it is no longer listed in the final version. Shaw et al. (2013) determined redshift limits of $0.14 < z < 2.2$. H.E.S.S. observed PKS 1440-389 for a total of $\sim$ 12 hr in the period Feb. 29 – May 27, 2012, which led to a detection with 9.1 σ significance. No evidence for significant γ-ray variability was found, and a simple single-zone leptonic SSC model (using the code of Böttcher et al. 2013) can fit the simultaneous SED (Figure 4 left) with parameters corresponding to a particle-dominated jet in which the ratio of powers carried in magnetic fields and relativistic electrons is $L_B/L_e \sim 0.1$.

4. The Gravitationally Lensed Blazar PKS 1830-211

Two *Fermi*-LAT detected γ-ray blazars (QSO B0218+357 and PKS 1830-211) are known to be gravitationally lensed by foreground galaxies. While the lensed images can not be spatially resolved by γ-ray observations, the light-travel time delay between the two images, in conjunction with the variable nature of these objects, can be exploited to look for the lensing-delayed counterpart of a γ-ray flare (Barnacka et al. 2011, Cheung et al. 2014). The lensing magnification along with the prospect of predicting the lensing-delayed second γ-ray flare, given the known time delay between the two images, motivated VHE observations of both of these blazars. In the case of QSO B0218+357 ($z = 0.94$), this led to the discovery of VHE γ-ray emission by MAGIC (Sitarek et al. 2015), making it the most distant known VHE γ-ray emitter at the time.

H.E.S.S. observations of the other lensed γ-ray blazar, PKS 1830-211, were triggered by the *Fermi*-LAT detection of a flare on July 27, 2014, which prompted H.E.S.S. observations in August 2014, around the time of the known radio delay of $\Delta t \sim 26$ days. Further motivation for H.E.S.S. observations was provided by studies of Barnacka et al. (2014b) that excess $\gamma\gamma$ absorption by intervening systems (the lensing galaxy or individual stars within it) is not expected to occur, thus enabling us to take full advantage of the expected lensing magnification to observe this $z = 2.5$ blazar. The H.E.S.S. observations did not result in a significant detection, and the resulting 99 % CL upper limits are compared to the *Fermi*-LAT spectra during the flare (green) and simultaneous to the H.E.S.S. observations (red) in Figure 4 (right). The comparison to the LAT flaring spectrum indicates a significant deficit of VHE γ-ray emission. This may be (at least partially) explained by strong EBL $\gamma\gamma$ absorption, but may also indicate a slightly different location of the VHE emission region compared to the HE emission region, which might lead to different time delays in the two energy regimes (Barnacka et al. 2014a).

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