RESULTS FROM H.E.S.S. OBSERVATIONS OF RELATIVISTIC SOURCES

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The High Energy Stereoscopic System (H.E.S.S.) is a southern hemisphere array of four Imaging Atmospheric Cherenkov Telescopes observing the sky in the very high energy gamma-ray range (E > 100 GeV). VHE observations are an invaluable tool to study the acceleration and propagation of energetic particles in many astrophysical systems where relativistic outflows are the main drivers of the emission, such as AGNs and galactic binary systems. In this paper the main results of the H.E.S.S. observations of these objects will be reviewed, and the general picture that emerges from them will be presented. We will also comment on prospects for future investigations with H.E.S.S.-II.

Keywords: VHE gamma-ray astronomy; Relativistic sources; Extragalactic jets.

1. Introduction

This paper is a short review of what we consider to be the most relevant results obtained by the H.E.S.S. collaboration from relativistic sources in recent years. We report on both galactic and extragalactic sources, concentrating on those objects whose behaviour most add to or most challenge our understanding of high-energy processes in astrophysics. Relativistic outflows are the environment of extreme physics per excellence, being the locus of multi-TeV particle acceleration in a number of distinct astrophysical systems. The rapidly developing field of ground-based gamma-ray astronomy provides a window into the very-high-energy (VHE; E > 100 GeV) universe, furnishing us with direct information on the populations of energetic particles in objects such as Active Galactic Nuclei (AGN), pulsar winds and galactic binary systems.

2. The High Energy Stereoscopic System

The H.E.S.S. array of four large (∼ 100 m² collecting area) Imaging Atmospheric Cherenkov Telescopes (IACTs), located in the Khomas highlands of Namibia (23.3°
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S.15.5° E; 1800 m a.s.l.), has been observing the sky since 2004.20 Ground-based gamma-ray instruments detect the Cherenkov light emitted by the secondary particles of γ-ray-initiated air showers. The array operates on the concept of a stereo-scopic system of IACTs, whereby multiple telescopes are used to simultaneously image the air showers from different viewing angles to improve energy resolution, reconstruction of the primary photon direction (∼0.05°–0.1°) and rejection of the dominant cosmic-ray background (> 99%). The H.E.S.S. camera F.O.V. of ∼5° is suited for imaging the (usually) extended galactic sources and facilitates the execution of extended surveys, such as that of the Galactic plane.13 The system is also capable of spectral measurements with an energy resolution of about 15%. With a post-background rejection energy threshold of ∼120 GeV, and an effective area of about \(10^5\) m² (both at Zenith), point sources with fluxes of the order of 10 mCrab \((3 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1})\) are detected within 50 h of observations.

3. Extragalactic Relativistic Sources

The rapidly populating TeV sky today numbers over 80 detected sources (see http://tevcat.uchicago.edu/), including a number of different object classes. Greater typological diversity is found amongst the Galactic population, where compact objects, binary systems and massive stars at late evolutionary stages figure as the primary sites of particle acceleration in the Galaxy. The extragalactic sources seen by H.E.S.S. are almost exclusively AGNs (10 BL Lacs + 2 FRI radio galaxies), the exception being the newly detected starburst galaxy NGC 253, whose emission is believed to originate from the combined activity of a large number of supernovae in its central regions rather than from nuclear activity.

3.1. PKS 2155-304 as viewed in TeVs

The high-frequency peaked BL Lac (HBL) PKS 2155-304 \(\text{R}(z = 0.116)\) has been a primary target for H.E.S.S. since the start of its operations, and four years of continual monitoring make it one of the best-studied extragalactic VHE source in the sky. Its brightness at TeV energies (∼0.15 Crab low flux state) guarantees the source is detected whenever observed by H.E.S.S., allowing the derivation of a well-sampled long-term light-curve which presents variability on timescales of days to years. Here we report on the source’s extreme outburst observed by H.E.S.S. in July 2006 and on observations performed jointly with the Fermi satellite in 2008.

3.1.1. Extreme outburst events in July 2006

The HBL PKS 2155-304 was detected by H.E.S.S. in an unusually high state throughout the month of July 2006, with an average baseline flux of about \(2 \times 10^{-10}\) cm\(^{-2}\) s\(^{-1}\), 5× higher than the typical low state for the source. Its activity peaked in two extreme flares observed on the nights of 28 and 30 July (MJD 53944 and 53946). The first flare \(\text{R}\) reached a maximum flux (> 200 GeV) of about 15.1 Crab,
almost 2 orders of magnitude above the low state, with a nightly average flux of \( \sim 1.7 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1} \). Intranight variability episodes with doubling timescales of \( \sim 2 \text{ min} \), the fastest ever seen for an AGN at any wavelength, were registered (see Fig. 1). The power spectrum distribution (PSD) showed significant variability above the noise level up to \( 1.6 \times 10^{-3} \text{ Hz} \) (600 s); the Fourier spectrum index of \( -2.06 \pm 0.2 \) indicates that most of the power is present at low frequencies and that the variability behaviour is compatible with a stochastic process. These PSD characteristics are very similar to those derived in X-rays for the same source, although the fractional rms variability amplitude is significantly higher in \( \gamma \)-rays.

Causality arguments bound the size \( R \) of the emission zone to the variability timescale \( t_{\text{var}} \) and the Doppler factor \( \delta \) of the flow. If the jets of blazars are indeed powered by accretion onto a supermassive black hole, the Schwarzschild radius of the central object sets the fundamental scale for the global dynamics of the system. The shortest value \( t_{\text{var}} \sim 170 \text{ s} \) registered implies a size for the emission region \( R\delta^{-1} \leq 4.65 \times 10^{12} \text{ cm} \leq 0.31 \text{ AU} \), so that for \( R > R_{S} \left( M_{\text{SMBH}} 1 - 2 \times 10^{9} M_{\odot} \right) \) Doppler factors as large as 50 are required, much higher than typically derived for blazars or what can be easily accommodated by theory. This unprecedented constraint on the location and dynamics of particle acceleration sites in extragalactic jets suggests that the VHE variability is not directly tied to the central engine and that the VHE emission originates from a distinct, more compact and energetic population within the flow.

On the second night of extreme variability, observations were conducted as part of a MWL campaign with Chandra; the VHE flux attained values comparable to those of the first flare. The intranight light-curve showed a large VHE outburst at the start of observations, which then faded along the rest of the night. The X-ray flux variability closely matched the VHE behaviour, whereas the simultaneous optical light-curve presented less variability and a more persistent high flux level. A novel and important feature of this night is the large Compton dominance of the source’s high state (\( L_{C}/L_{S} \sim 8 - 10 \)), which is apparent in the SED of Fig. 2.
Fig. 2. Spectral Energy Distribution of PKS 2155-304. Left: Low-state SED during simultaneous H.E.S.S. and Fermi observations; the continuous curve is a single-zone SSC model fit to the SED (with $\Gamma \sim 30$ and $B \sim 0.02$). The red-dashed and the dot-dashed lines are for the same model without electrons above $\gamma_1 \sim 1 \times 10^4$ and $\gamma_2 \sim 2 \times 10^5$. Right: Simultaneous X-ray/VHE high-state SED for the night of 30 July 2006; notice the Compton dominance during the high state and the presence of no shifts on the overall SED peaks during variability

this feature evolves during the decaying phase of the flare towards the more usual value of 1 at lower fluxes. This is the first time Compton dominance is observed in a HBL, suggesting a bimodality in the flaring mode of this kind of source: either synchrotron or Compton dominated. Additionally, a cubic relation is observed in the evolution of the flare between the VHE and X-ray fluxes ($F_\gamma \propto F_X^3$) which cannot be accounted for by a single-zone SSC model. Both these properties indicate that the entire SED behaviour could result from a superposition of two emission zones: a steady component, responsible for the “persistent” emission, and a more compact one, with larger bulk motion, responsible for the flaring activity via an external Compton channel in the interplay between different parts of the jet.

3.1.2. H.E.S.S. and Fermi observations of the quiescent state in 2008

In August 2008, the H.E.S.S. and Fermi collaborations combined efforts in a MWL campaign to sample the full Inverse-Compton SED of a TeV blazar, observationally constraining for the first time the peak of the IC bump. During this campaign PKS 2155-304 was found to be in a quiescent state in VHE. The fractional rms variability above 200 GeV was $\sim 23\% \pm 3\%$, and simultaneous X-ray RXTE data also presented variations with flux doubling episodes in timescales of days; the optical and the 0.2-300 GeV Fermi fluxes showed no significant variations during the 11 nights of the campaign. The optical-to-TeV time-averaged SED of the source was modelled by a single-zone SSC model which broadly fits the entire profile (see Fig. 2); the model parameters used for the fit match those of an SSC description of a steady large jet component for PKS 2155-304. A detailed study of the model reveals that the most energetic electrons in the system are responsible for the X-ray emission. These electrons do not contribute to the GeV-to-TeV IC emission due to
3.2. H.E.S.S. Observations of Radio Galaxies

The detection of γ-rays from distant extragalactic objects is possible due to effective acceleration and Doppler boosting of the radiation in relativistic outflows; in the absence of this boosting, such as in misaligned-jet sources, only extremely powerful, “isotropic” sources are expected to be detectable at VHE energies. Nearby radio-galaxies (< 100 Mpc) such as M 87 (φ_1.o.s. ~ 20°-40°) and Cen A (φ_1.o.s. > 15°) are part of this category, and have recently been established as VHE emitters. The importance of observing nearby sources at high-energies is that they provide a unique opportunity to probe the origin of the VHE emission with unprecedented spatial resolution. Given the similarity among the systems, this might add to our understanding of gamma-ray emission in more distant AGNs such as blazars.

3.2.1. M87: a laboratory for jet and AGN physics

M 87^1 (16 Mpc; \( M_{\text{MBH}} \sim 3 \times 10^9 M_\odot \)) was the first radio-galaxy observed at VHE energies,^2 for which H.E.S.S. detected a point-like γ-ray signal in positional
coincidence with the central regions of the object\cite{14}. Although the source is close enough for the PSF of the telescopes to exclude the outer lobes as the site of the emission, the 3 arcmin size upper limit for the TeV source is consistent with several potential sites of particle acceleration and $\gamma$-ray production, including the central AGN and different regions of the inner kpc-scale jet\cite{5}. Observations of the source since 2003\cite{14,32} displayed flux variability on scales of years and days, constraining the size of the $\gamma$-ray emission site to be very compact (with a size U.L. \(< 100R_S\)) and therefore probably located in the vicinity of the central engine.

The first VHE flare in 2005 was detected during an exceptional, long-term high X-ray state of the knot HST-1, some 60 pc ($\sim 1^\prime$) from the radio nucleus of the jet\cite{8}, but without unambiguous suggestion of a direct correlation existing between the two events. Further investigations were conducted in a coordinated H.E.S.S., MAGIC and VERITAS campaign in 2008, in which a stronger flux outburst with variability timescales of days was clearly detected\cite{32}. Contemporaneous 43 GHz radio VLBA\cite{34} and X-ray Chandra\cite{9} observations were also conducted (see Fig. 2). Unlike 2005, HST-1 was in a low X-ray state whereas the core showed a flux increase peaking around the time of the maximum of the TeV activity. Enhanced radio activity was also present in the core and the VLBI images recorded the emergence of a new knot happening contemporaneously to the flare at high energies. These more recent MWL results suggest that the TeV emission in M 87 takes place in the immediate surroundings of the SMBH, well within the jet collimation region\cite{23} (the radio core is $\sim 100R_S$ downstream from the central engine).

3.2.2. H.E.S.S. detection of Centaurus A

H.E.S.S. has recently reported the discovery of VHE $\gamma$-ray emission from the radio galaxy Centaurus A\cite{22} (3.8 Mpc), the nearest active galaxy to Earth. The signal flux of $\sim 8$ mCrab ($L = 2.6 \times 10^{39}$ erg s$^{-1}$) is associated with a region including the radio core, kpc jets and the inner radio lobes\cite{18}, the best fit position being well compatible with the innermost regions: a scenario similar to the picture we have for M 87.

4. Variable Galactic Sources

LS 5039\cite{10} and PSR B1259-63\cite{11} are the only two variable galactic TeV sources detected by H.E.S.S. unambiguously associated with compact binary systems. The two systems differ in the nature of the compact object: whereas PSR B1259-63 is known to be a “binary plerion”, it is debatable if in LS 5039 it is a spinning neutron star or a black hole that is orbiting the massive companion\cite{7}. These two possibilities leave the interpretation open as to whether the TeV emission results from pulsar wind interaction as in PSR B1259-63 or if it is the product of accretion, and we are therefore seeing the first observational evidence of TeV emission from microquasars. In the latter scenario, emission would come from relativistic jets of
particles emanating from the BH-accretion disc system in an analogous way to what happens in active galaxies.\textsuperscript{28}

An interesting feature of the observations of these objects is that their fundamental timescales are dictated by the orbital period of the binary system (days-years), since the high magnetic fields involved (up to \( \sim \) 1 G) imply rapid electron cooling rates: one expects therefore the emitted flux to more or less reflect the (radically different along the orbit) “instantaneous” environment of the system and the variability is modulated according to the orbital configuration (i.e. apastron-periastron passages). In fact, for both systems such modulation has been observed.\textsuperscript{12,26}

Details of such variability depend on three factors: the radiation and absorption mechanisms and the geometry of the system. In the case of LS 5039, for which radio images suggest the presence of a jet\textsuperscript{29}, the observed flux peaks at inferior conjunction, when the compact object passes in front of the massive companion. Flux variation is accompanied by spectral variability, mostly probably as a result of \( \gamma \)-\( \gamma \) pair production on the radiation field of the massive companion. Nevertheless, a simple picture where orbital modulation is solely the result of absorption cannot explain the detailed features of the observation: the maximum spectral modulation is expected to happen at around 300 GeV (temperature of the companion photon field \( \approx \) 3 eV) whereas the observed variation peaks at 5 TeV, with little signature of variability at the predicted energy. Additionally, the flux at superior conjunction is not zero, despite the expected high density of the intervening photon field, and it remains to understand if this residual flux is due to a particular geometrical configuration and/or the result of direct observations of IC electromagnetic cascades.\textsuperscript{7}

Due to the high eccentricity of the orbit, the period of PSR B1259-63 is relatively long (\( \approx \) 3.4 years), and the system was observed by H.E.S.S. during two periastron passages, in 2004\textsuperscript{11} and 2007\textsuperscript{26} (it is not detectable for orbital phases \( \phi \gg \pm 0.1 \)). The knowledge that it is a pulsar orbiting the massive companion constrains the emission to be the result of pulsar-wind interaction with the massive star’s photon field. The variable light-curve of the source shows peculiar behaviour, with two maxima around a month before and after periastron passage. Mechanisms such as IC scattering on the massive companion’s photon field\textsuperscript{27} or hadronic scenarios\textsuperscript{25} (e.g. \( pp \rightarrow \pi^0 \rightarrow \gamma \gamma \)) have both been suggested as possible origins for the TeV photons. But the most recent observations for the 2007 periastron passage, have detected an early (\( \phi > 0.05 \)) excess in the VHE flux which introduce new difficulties for both approaches. The next periastron passage will happen around October 2010.

5. Prospects and Final Remarks

H.E.S.S. has observed a number of different sources and source categories whose emission is powered by particle acceleration in relativistic outflows. Many of these objects are potential candidates for being sources of Galactic and extragalactic cosmic-rays. Despite improvements on our understanding of the origin of \( \gamma \)-ray emission in the universe, the results presented here pose a similar number of new
and deeper questions on the nature of relativistic sources. H.E.S.S.-II is expected to greatly contribute to this work. The addition of a larger telescope to the centre of the array will decrease the energy threshold of the system to $\sim 15 - 25$ GeV and improve the sensitivity of the instrument by a factor of 1.5 to 2 at higher energies.

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