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The H.E.S.S. Experiment:
Current Status and Future Prospects

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In the 15 years since its construction, the H.E.S.S. gamma-ray observatory has allowed the study of the very-high-energy gamma-ray sky at unprecedented resolutions and sensitivities. During this period H.E.S.S. has discovered a rich zoo of both galactic and extra galactic source classes, made measurements of the galactic diffuse gamma-ray emission and galactic cosmic-ray energy spectrum and placed limits on fundamental physical processes. H.E.S.S. took an important part in the current emergence of multi-messenger, multi-wavength astronomy that is currently revolutionizing our view on the high-energy universe. In this context, a formal decision on the prolongation of H.E.S.S. for a minimum of three years was made in January 2019, together with an upgrade of the camera of the large telescope.

In this contribution, a summary of the latest H.E.S.S. results will be presented, describing the most interesting new observations and their physical interpretation. I will detail the latest and upcoming upgrades and improvements to the H.E.S.S. hardware and data analyses and the future science prospects for the experiment.

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1. Introduction

The High Energy Stereoscopic System (H.E.S.S.) is an array of five imaging atmospheric Cherenkov telescopes (IACTs) which is situated in the Khomas Highland of Namibia (S 23°16′18″, E 16°30′00″) at an altitude of 1835 m above sea level. H.E.S.S. is sensitive to very high-energy (VHE) gamma rays in the energy range of $\sim$ 30 GeV to about 100 TeV (see Figure 1). These gamma rays are absorbed in the atmosphere, where they create a short-lived shower of particles. The telescopes detect the faint, short flashes of Cherenkov light which these particles emit by reflecting the light onto extremely sensitive cameras. Each camera image gives the position on the sky of a single gamma-ray photon, and the amount of light collected gives the energy of the initial gamma ray. Building up the images photon by photon allows H.E.S.S. to create maps of the gamma-ray sky.

Operating H.E.S.S. as the first hybrid array of IACTs

H.E.S.S. started observations as a system of four IACTs in 2003. The telescopes, named CT1-CT4 hereafter, are placed in a square formation of 120 m side length and each telescope comprises a 107 m^2 reflector and an imaging camera that is instrumented with 960 photomultiplier tubes (PMTs), creating a 5° field of view on the sky. The overall performance of the 4-telescope array is described in [1].

In 2012, a fifth telescope was added to the center of the array. The main goal of this telescope, called CT5 hereafter, was to lower the energy threshold of the array from 100 GeV down to about 30 GeV. For this reason, CT5 has a large mirror area (614 m^2), photosensors with higher quantum efficiency and a reduced dead-time compared to CT1-4 (see [2]), allowing CT5 to trigger on air showers with a rate of $\sim$ 3 kHz. This is about ten times the event rate of the CT1-4 telescopes and leads, together with the low-energy threshold, to air shower events that are triggered by CT5 alone. Therefore, the array trigger of H.E.S.S. is configured to accept all events which triggered at

Figure 1: Picture of H.E.S.S. with the four 12-m telescopes of Davies-Cotton design and the 28-m parabolic-dish telescope in the middle of the array.

least two of the five telescopes (stereoscopic mode) or CT5 alone (monoscopic mode). This makes H.E.S.S. the first successfully operated hybrid array of IACTs worldwide.

Upgrading the 14-years-old cameras to improve their reliability and overall performance

In order to further improve on the hybrid array performance of H.E.S.S., the cameras of the four 12-m telescopes underwent a substantial upgrade in 2015/16 [3]. One of the main reasons for this upgrade was to enable the CT1-4 telescopes to trigger at a lower threshold, resulting in more events being recorded stereoscopically together with CT5. This could not be achieved with the original cameras [4] as their rather large readout time of $\sim 450\ \mu$s per event did not allow for a substantial lowering of the trigger threshold without significant event losses. To additionally also reduce the system failure rate and improve on the maintainability and realiability of the cameras, the upgrade involved replacing all camera components except for the PMTs (see Figure 1). This also included a new mechanical design of the cooling and ventillation system.

To allow for a much lower dead time, the front-ends of the upgraded cameras were built around the NECTAr chip [5], developed for the next generation of IACTs. Additionally, new hardware for the back-end electronics was developed including the camera trigger, power-supply and clock distribution. The entirely replaced camera electronics is now fully controlled and read out via Ethernet using a combination of FPGA and embedded ARM computers. This allowed for a reduced dead time of $\sim 7\ \mu$s per event at even higher trigger rates (see Figure 1) and thus substantially increased the number of stereoscopic events read out together with CT5 from $\sim 15\%$ to $\sim 35\%$. Furthermore, the new camera electronics also enabled the readout of full waveforms which is used to improve both low- and high-energy performance (see [6]).

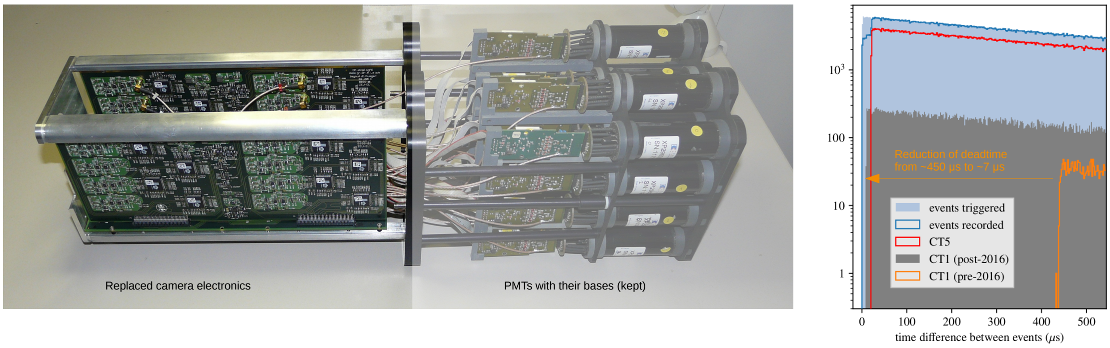

Figure 2: (Left) Picture of one of the 60 camera units composed of 16 PMTs each for which the electronics has been fully replaced during the upgrade in 2016 while the PMTs and their bases have been kept. (Right) Trigger performance of the H.E.S.S. cameras, clearly showing the much higher rates of CT5 compared to CT1 and the siginificant reduction of dead time of the upgraded CT1 camera, allowing also to operate at higher trigger rates without event losses.

Replacement of the onsite DAQ cluster infrastructure in summer 2019

Over the more then 15-years of lifetime of the experiment, multiple components of the H.E.S.S. data acquisition (DAQ) and IT infrastructure onsite have reached their end-of-life status by which they have lost vendor support and are no longer tested for compatibility with currently produced hardware. In the context of the prolongation of the operation of H.E.S.S. beyond 2019, various upgrade scenarios were explored. It was finally decided that a full cluster replacement is the most effective way to make the DAQ system future-proof and minimize the risk of hardware failures.

The DAQ cluster upgrade included the replacement of all display machines necessary for stable real-time monitoring of the system during operation as well as the replacement of subsystems including storage, computing nodes, system- and routing servers and network. It provides now all functionality of the replaced subsystems and resulted in a fully homogeneous and state-of-the-art system which minimizes long-term maintenance efforts.

2. Scientific highlights

Since its commissioning in 2003, H.E.S.S. has discovered more then 100 VHE sources, covering a rich zoo of both galactic and extra galactic source classes. Furthermore, H.E.S.S. made measurements of the galactic diffuse gamma-ray emission and galactic cosmic-ray energy spectrum and placed limits on fundamental physical processes. A selection of recent results and scientific highlights is given in the following.

Galactic science with 15 years of H.E.S.S. data

Since 2003, the H.E.S.S. telescopes have continuously surveyed the galaxy and targeted specific sources in the Milky Way, making discoveries of new sources and object classes. In 2018, this programme has culminated in the publication of a series of papers in a special issue entitled *"H.E.S.S. phase-I observations of the plane of the Milky Way"* [7], including the updated H.E.S.S. Galactic Plane Survey (see Figure 3). This is not only the deepest view of the inner part of our galaxy at extreme energies, it allowed also studies of the populations of pulsar wind nebulae and supernova remnants, as well as the search for new object classes unseen before in VHE gamma rays such as microquasars or shocks around fast-moving stars. These studies are complemented by precision measurements of shell-type supernova remnants such as RX J1713-3946 and diffuse emission at the centre of our Galaxy, reveiling detailed properties of the underlying particle accelerators and shed new light on how cosmic rays move through the interstellar medium and shape their environment.

In the past years, the science focus has shifted towards more detailed studies of the morphology, spectral properties and temporal variability of individual sources. This allows us to investigate the high-energy end of the spectra of hard-spectra sources to help identifing PeVatrons, the sources of the Galactic Cosmic Rays with energies up to the knee, and enables time-resolved measurements to investigate the periodic emission from gamma-ray binaries at time-scales of years down to days as well as the study for VHE gamma-ray emission from pulsars. An overview of the newest results will be presented at this conference [8].

Unveiling the secrets of the radio galaxy Centaurus A through precision measurements

Centaurus A is the nearest radio galaxy ($d \simeq 3.8$ Mpc). This allowed for detailed morphological studies at different wavelengths, reveiling a variety of structures: a radio-emitting core, a parsec-scale jet and counter-jet system, a kiloparsec-scale jet and inner lobes, up to giant outer lobes with a length of hundreds of kiloparsecs (see Figure 3).

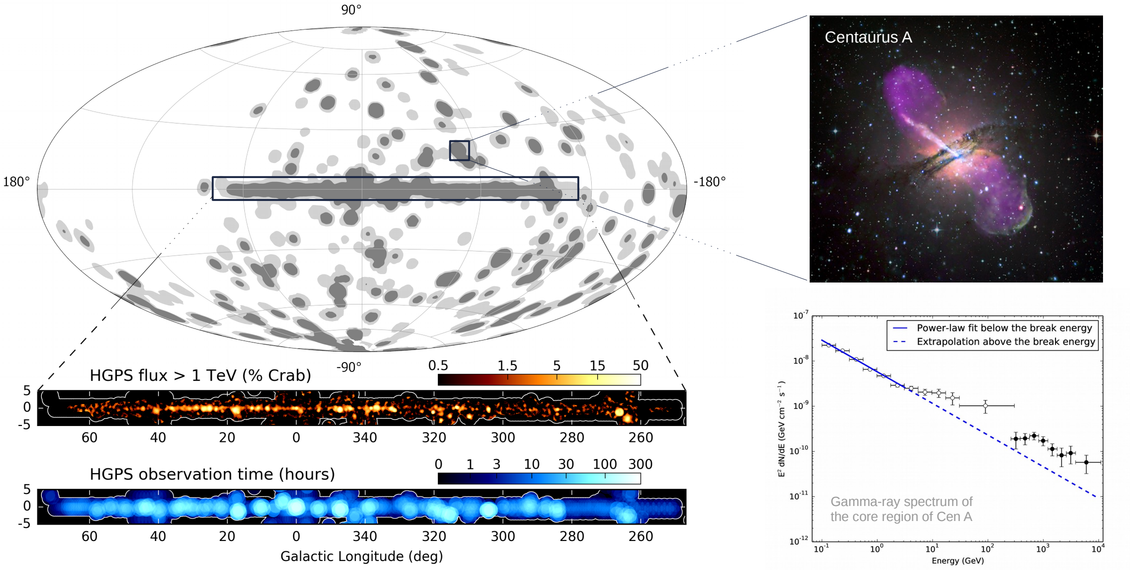

Figure 3: (Left) H.E.S.S. all-sky exposure map of observations with more then 30 min (light grey) and $>$ 10 hours (dark grey) below which the H.E.S.S. Galactic Plane Survey maps from [9] are shown. (Right) Composite multiwavelength image of the radio galaxy Centaurus A (Credits: X-ray: NASA/CXC/CfA/R.Kraft et al; Radio: NSF/VLA/Univ.Hertfordshire/M.Hardcastle; Optical: ESO/WFI/M.Rejkuba et al.) below which the gamma-ray spectrum above 100 MeV is shown (adopted from [10]).

In the gamma-ray regime, Centaurus A has been detected both by Fermi-LAT and H.E.S.S. and the analysis of the combined data set displays a complex spectral energy distribution (SED) of the core region of this source [10]. While in the H.E.S.S. energy range above 250 GeV the energy spectrum is compatible with a power-law, the Fermi-LAT analysis provides clear evidence of a spectral hardening above a break energy of about 3 GeV. This spectral hardening, and the fact that the VHE flux exceeds the simple power-law extrapolation of the low-energy Fermi-LAT spectrum, disfavours a single-zone self-synchrotron Compton interpretation for the overall SED of the core.

While a variety of different interpretations are available to explain the additional gamma-ray emitting component, its physical origin could not yet be resolved due to instrumental limitations in angular resolution and the apparent absence of significant variability in both the HE and VHE data. However, improved analysis methods and simulation efforts developed within the VHE gamma-ray community (e.g. [11]) allowed more detailed studies of the H.E.S.S. data set and will be presented at this conference.

The successful story of more then 10 years of follow-up observations of GRBs with H.E.S.S.

Gamma Ray Bursts (GRBs) are among the most violent phenomena known in the universe and are seen as short (from 0.1 s up to few hundred seconds), intense periods of gamma-ray emission in the keV to MeV energy range. After this intense prompt emission phase the emission decays on longer timescales, the so-called afterglow phase, during which counterparts at different wavelengths are commonly detected. Detections at high-energy gamma rays ($>$ 10 GeV), however, are very rare and challenge the widely used *fireball model* [12] to explain the emission. The huge effective area of IACTs compared to satellite instruments like *Fermi*-LAT allows for GRB counterpart searches with several orders of magnitudes better sensitivity on short timescales at energies around 100 GeV. A detection of a GRB at these energies would therefore further challenge our current understanding of the GRB phenomenon and would provide a deeper insight into particle acceleration in GRBs.

Since 2008, H.E.S.S. has performed around 68 follow-ups of GRB alerts under various observation conditions. Among these, 39 bursts have been observed with CT5, allowing for the lowest possible energy threshold. Until August 2018, no VHE gamma-ray emission could be detected by H.E.S.S., neither in the prompt nor during the afterglow phase of the bursts [13]. However, these observations helped to constantly improve the follow-up strategy and resulted recently in the detection of GRB180720B by H.E.S.S. This detection, together with one from MAGIC [14], opens a new era in understanding the energetics and the origin of VHE gamma-ray emission of GRBs.

Probing the magnetic field in the GW170817 outflow using long-term follow-up observations

In the last years, multi-messenger astronomy has made a huge step forward with the detection of gravitational wave (GW) signals from black hole and neutron star mergers. The unprecedented follow-up observation campaigns in the entire electromagnetic spectrum, launched after the dectection of a GW produced by a neutron star merger in August 2017, enabled the detection of the first electromagnetic counterpart to the binary neutron star (BNS) merger remnant GW170817. This established the connection between short GRBs and BNS mergers as well as confirmed the forging of heavy elements in the ejacta (a so-called kilonova) [15]. The brightening of the non-thermal radio and X-ray emission, however, came with some surprise and lasted more then 100 days (see Figure 4). This behaviour is indicative of efficient particle acceleration in the merger remnant and became dominant over the fading UV, optical and infrared emission after ~ 9 days.

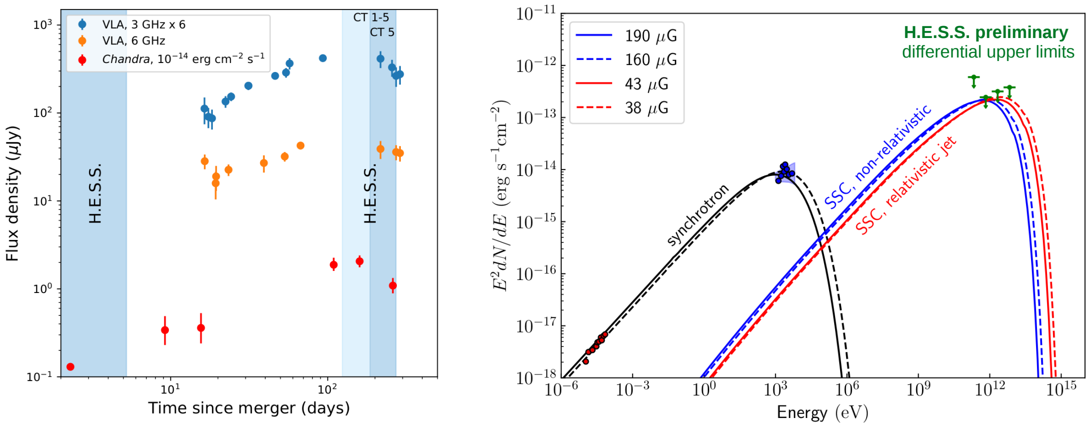

Figure 4: Results of the H.E.S.S. observations of GW170817. (Left) X-ray and radio lightcurves (adopted from [16]) overlayed with the H.E.S.S. observation windows. (Right) Spectral energy distribution $\sim$200 days after the merger with the two different SSC scenarios described in the text.

H.E.S.S. promply reacted to this GW alert thanks to its fully automatic alert system [17] and observed the region around GW170817/GRB170817A as the first ground-based observatory.

While no significant VHE gamma-ray emission could be detected during the prompt phase [18], the brightening of the non-thermal emission triggered deep follow-up observations from 124 to 272 days after the merger. The resulting upper limits can be used to constrain the magnetic field in the merger remnant, assuming that the inverse Compton emission is SSC in origin. Under the assumption that the remnant expands isotropically and non-relativistic, the (preliminary) H.E.S.S. upper limits constrain the minimum magnetic field strength to $160-190\ \mu$G. On the other hand, in a relativistic scenario where a relativistic jet is launched, the lower limit is weakened to the level of $\sim 40\ \mu$G (see Figure 4). This demonstrates that by measuring VHE gamma rays we would be able to probe directly the magnetic field in BNS merger remnants and can thus break the ambiguity between energy in electrons and magnetic fields arising from the measurement of the synchrotron part of the SED alone.

3. Future Prospects

H.E.S.S. is the world's first hybrid IACT system, combining telescopes of different mirror area (and therefore different energy thresholds), and will stay the only such system until the start of CTA. The H.E.S.S. instrument as a whole is operating rather smoothly for more then 15 years now. Thanks to ongoing improvements of hardware and reconstruction methods, it is ideally suited to explore the gamma-ray sky at very-high energies even deeper in the coming three years for which operation of H.E.S.S. has recently been extended.

Observations with H.E.S.S. will continue to explore a rich zoo of key science topics, covering both deep (>100 hours) observations of a few known sources and observations in the field of time-domain multi-wavelength/multi-messenger astronomy. Among the first category are the search for Pevatrons, deeper investigations of the high-energy tails of pulsars, as well as the completion of the scan of the inner galaxy to search for dark matter signals with an unprecedented sensitivity. In the time-domain, the scientific program of H.E.S.S. contains an ever increasing fraction of projects, including Target of Opportunity (ToO) observations as well as monitoring programs. Thanks to its low-energy (<100 GeV) threshold and huge capabilities for rapid follow-up observations using a fully automatic ToO system, astrophysical transients can be triggered through a large variety of chains, including all parts of the electromagnetic spectrum, gravitational waves and high-energy neutrinos, promising major breakthroughs in the currently dawning era of multi-messenger astronomy. Furthermore, many new facilities open new opportuninities for synergetic studies (e.g., X-ray facility NICER, the radio observatories MeerKAT, ASKAP and MWA, or the optical transient factories ZTF and LSST). This novelty also implies that many of the monitoring projects[1] have never been done before and are fully exploratory, enabling H.E.S.S. to explore new science questions.

In view of the ambitious science program and the exceptional role of H.E.S.S. as the only IACT in the southern hemisphere, the H.E.S.S. collaboration is currently investigating operations of the instrument during partial moon or twilight to maximise the available observation time and to avoid losing important multi-wavelength opportunities. Furthermore, towards the end of 2019, the CT5 camera will be replaced by an advanced prototype of the FlashCam camera [19], developed

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[1] The monitoring program of H.E.S.S. includes follow-up monitoring of events that are expected to give rise to delayed gamma-ray emission (e.g. on GW170817), known or expected gamma-ray sources that vary on longer time scales (e.g. SN 1987A, Eta Carina) and coordinated multi-frequency observations (e.g. AGN).

for operation on the middle-sized telescopes of the CTA observatory [20]. This latest upgrade to H.E.S.S. will allow for efficient operation of CT5 together with the already upgraded CT1-4 cameras during the forthcoming years. Further performance improvements are expected from ongoing improvements on the analysis and reconstruction chains which will allow H.E.S.S. to continue making world-leading scientific contributions in the coming years.

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