Extragalactic Observations with HESS: Past and Future

Andrew M. Taylor on behalf of the H.E.S.S. collaboration*
Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland
E-mail: taylora@cp.dias.ie

David Sanchez
Laboratoire d’Annecy-le-Vieux de Physique des Particules, Université Savoie Mont-Blanc,
CNRS/IN2P3, F-74941 Annecy-le-Vieux, France
E-mail: david.sanchez@lapp.in2p3.fr

Matteo Cerruti
Laboratoire de PhysiqueNucléaire et de Hautes Energies (LPNHE), 4 place Jussieu, F-75252,
Paris Cedex 5, France
E-mail: mcerruti@lpnhe.in2p3.fr

The present H.E.S.S. II era of the H.E.S.S. collaboration follows from the successful upgrade of the H.E.S.S. array, and the first published results obtained with this new instrument. Thanks to these achievements, a lower energy threshold with H.E.S.S. II than that obtained previously with H.E.S.S. I has been clearly demonstrated. The success of these developments has now opened up a whole new lower-energy window to the Universe. I here explore, from the extragalactic point of view, both what has been learnt so far from the H.E.S.S. observations through this new window, and postulate also on what else might still be seen beyond this. I will firstly reflect upon the AGN result highlights, obtained using the new H.E.S.S. II instrument. Specifically, the rise in detections of bright FSRQ AGN with H.E.S.S. II will be addressed [eg. PKS 0736 (z≈0.19), PKS 1510 (z≈0.36), and 3C 279 (z≈0.54)]. Hand in hand with this recent progress, the benefits brought to our efforts to observe GRBs through both access to this new lower energy window, and the quick instrument response to ToO alerts, will be covered. Furthermore, the potential for the discovery of new transient phenomena in the H.E.S.S. II era will also be emphasised. Lastly, the question as to lessons learnt from previous H.E.S.S. I AGN results about the intrinsic source spectra, primarily focusing on the HBL class, will be considered.

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*Speaker.
1. Introduction

Extragalactic high energy gamma-ray astronomy has developed from an emerging discipline into a fully fledged research field over the past several decades. Following its initial success in the 1990s with the first AGN discoveries of Mrk 421 and Mrk 501 [1, 2], the field now boasts the detection of more than 60 AGN at very high energies (VHE) by ground-based gamma-ray instruments 1.

A consequence of these observational achievements has been a broadening in the array of different AGN subclasses, believed to represent various manifestations of a single (few) AGN type(s) [3], at these energies. These range from the bright beamed blazars of both BL Lac and flat spectrum radio quasar (FSRQ) type, the most numerous observed AGN subclass at VHE, to their dimmer weakly beamed/unbeamed counterparts, radio galaxies.

The jet-beamed blazar family members, are observed as point-like sources. For these, information about the spatial extent of the emission site may be encoded into the temporal structure of the flux that they emit. Indeed, the most challenging/enlightening results from observations of such temporal structure information, come from the most intense outbursts (such as that of PKS 2155-304 [4] in 2006). Such extreme bright episodic emission has lead to tight constraints being placed upon the size of the emission region and the jet Doppler factor.

At present, H.E.S.S., based in Namibia, is one of the principal stereoscopic Cherenkov telescope instruments currently in operation. This sensitive stereoscopic Cherenkov telescope instrument provides a unique VHE perspective on the southern hemisphere regions of the sky. The achievements of this instrument have played a key part in bringing about the present flourishing status of the field. Furthermore, an upgrade of this experiment through the completed installation of a massive 28 m telescope at the centre of the original array in 2012, marked the onset of the H.E.S.S. II era. This upgrade resulted in significant improvements in the instrument’s low energy sensitivity, reducing significantly its threshold energy [5].

Recent years have also seen the arrival of new monitoring instruments, with FACT [6], and the now completed HAWC-300 [7], collectively able to provide wide field of view and sensitive effective AGN monitoring. The complementarity provided by the monitoring and follow-ups through both the broad sky coverage, and the in-depth low energy threshold targeted observations, make promising the prospects for further growth in the coming years. Such collaborative efforts allow what may be obtained from this present generation instrument to be maximised before the arrival of the next generation CTA north and south instruments [8].

In the following, several of the key recent H.E.S.S. observational developments in AGN gamma-ray astrophysics will be covered. In section 2, a discussion on the dawn of the new H.E.S.S. II era will be addressed. Starting in subsection 2.1, the first H.E.S.S. II era results will be presented, noting in particular the rise of the detection of FSRQ type blazars. In subsection 2.2 current efforts utilising wide field-of-view VHE AGN monitoring instruments as efficient trigger alerts will be discussed. Following this, subsection 2.3 considers potential new sources which may be detectable within the new H.E.S.S. II era. Lastly, in section 3, a summary of the lessons learnt about the intrinsic spectra of AGN (primarily HBL) detected by H.E.S.S. I will be presented. The conclusions to this discourse will be provided in section 4.

1See http://tevcat.uchicago.edu for an up-to-date list.
2. HESS II Era

Since October 2012 a fifth telescope at the centre of the original H.E.S.S. array, has been operational, taking data in coordination with the other H.E.S.S. I telescopes. This five telescope set-up is referred to as H.E.S.S. II. The analysis of the data taken in this new setup may be made either utilising the information from all of the telescopes (hybrid), or utilising only the information from the fifth telescope (mono), [16], each providing niche advantages depending on the source type.

One of the recent H.E.S.S. II highlights which utilised the hybrid analysis was the detection of a new extreme HBL candidate, 1RXS J023832.6-311658. Little is presently understood about this class of object, which demonstrates a continuation of its high energy (HE) hard spectral index into the VHE domain, without evidence for a cutoff. Furthermore, this blazar class appears to show little evidence of variability in their lightcurves, and curious evidence of correlations found have suggested that preferred directions of these sources exist long “voidy” lines of sight [17]. Such limitations in our understanding of this class, in part, is due to the small number of such objects so far having been discovered, highlighting the need to search for more such objects.

The first H.E.S.S. II AGN results which utilised the mono analysis came from observational campaigns taken with this new setup in 2013 and 2014. These observations were of the HBL blazars PKS 2155-304 and PG 1553+113, which were both found to be in quiescent states during the observation periods [9]. Despite these lowered activity levels, significant achievements in lowering the threshold energy utilising the new fifth telescope (mono) data, with analysis of this data for the PKS 2155-304 and PG 1553+113 observations reaching down to new threshold energies of 80 GeV and 110 GeV, respectively.

2.1 The Rise of the FSRQs

Building on the successful achievement of a lower energy threshold analysis utilising the H.E.S.S. II, a wider spread of blazar classes (eg. HBLs, LBLs, FSRQs) and redshifts, has become accessible to the instrument. Indeed, further proof of the successful lowering of the threshold energy of analysis utilising H.E.S.S. II mono data comes from the observations 3C 279, which underwent a giant outburst back in July 2015. H.E.S.S. II mono analysis of these observations of the flare achieved a record low energy threshold energy of 66 GeV for AGN results with this instrument. Fig. 1 shows the HESS and Fermi components of its SED of during the second night of the flaring outburst. Along this same vein, the detection of second FSRQ, PKS 0736+017, which underwent an outburst in February 2015, was also achieved utilising the analysis of H.E.S.S. II data. Again, H.E.S.S. II mono analysis of these observations achieved an energy threshold of 80 GeV.

Lastly, observations by both H.E.S.S. and MAGIC of giant flare from another FSRQ, namely PKS 1510-089, which underwent an massive outburst in May 2016, collectively provided exceptional temporal coverage of the flaring event at VHE.

For all three of these FSRQ flares, the detection of VHE emission from them during their outbursting episodes presents new surprising and unexpected challenges for their modeling. Specifically, the presence of the broad line region (BLR), an intense radiation field in the vicinity of the AGN, presents a barrier for the escape of VHE emission from within it. In turn, the detection of VHE emission from these sources can be used to place strong constraints on the position of the
emission site with respect to the BLR location [10]. With gamma-ray emission beyond 200 GeV detected from each of these systems during their outbursts, the emission site is found to be constrained to sit at a distance beyond \( r_{\text{BLR}} \approx 10^{17} \text{ cm} \left( \frac{L_{\text{disk}}}{10^{45} \text{ ergs}^{-1}} \right)^{1/2} \) [11], where \( L_{\text{disk}} \) is the thermal luminosity of the accretion disk.

Information about the spatial size of the emission site, from where the outburst originates, is also provided by the minimum temporal variability time-scale in the observed lightcurve. During their recent outbursts, unexpectedly short time-scale variability have been revealed for both objects. Specifically, for 3C 279, \(~\)minute time-scale variability in the \( >100 \text{ MeV} \) HE lightcurves was discovered [12]. Likewise, at VHE, for PKS 1510-089 \(~\)tens of minute time-scale structure.

Together, both the lack of internal absorption features in the flaring FSRQ spectra, and the short variability time-scales observed during the flare, make for rather challenging constraints. Reconciliation of these two differing results only appears to be possible in a few possible scenarios. The first is if the emission site sits sufficiently far out such that absorption of the BLR is avoided, potentially allowing the intrinsic spectrum to continue as an extrapolation of that in the \( \text{Fermi-LAT} \) domain. The second is if the emission originates from only a small subsection of the jet, out at distance scales beyond the BLR.

### 2.2 An AGN Transient Machine

To fully exploit the lowered threshold energy to observe the larger assortment of VHE AGN in the high redshift Universe demands efficient wide-field coverage of the transient VHE sky. To this end, full advantage is being made of broad multi-wavelength transient event monitoring. In particular, the H.E.S.S. collaboration is provided with alerts at optical, X-ray, HE gamma-ray, and VHE gamma-ray energies. Indeed, for the three AGN discussed in the previous section, 3C 279, PKS 0736+017, and PKS 1510-089, \( \text{Fermi-LAT} \) triggers and a H.E.S.S. trigger during a monitoring campaign, instigated the subsequent in-depth observations during their heightened activity states.

A further example of such effective transient observations is provided by the H.E.S.S. observations of Mrk 501 in June 2014. These observations were triggered by FACT, an imaging air Cherenkov telescope (IACT) which regularly monitors the activity of known VHE AGN, provid-
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Figure 2: The observed spectral data points of Mrk 501 above 300 GeV, from observations taken both before and during its extremely bright outburst in June 2014 [13].

ing alerts for follow-up observation to the VHE gamma-ray community. During a giant outburst in 2014, the flux level of Mrk 501 observed by H.E.S.S. matched that of the record level, observed by HEGRA back in 1997 [14]. The obtained spectra both during this flare, and in the quiescent state, are shown in fig. 2. Of particular note from these results is that the spectrum observed during this flare, once extragalactic background light (EBL) absorption had been accounted for, showed no signs of a cutoff, continuing as a hard spectrum up to the highest energy data point (∼ 20 TeV).

2.3 New VHE Transient Sources

Alongside the broadened AGN discovery potential which the onset of the H.E.S.S. II era has opened up, the possibility to catch new VHE phenomena has also been increased. Indeed, a consideration of the competing sensitivities of Fermi-LAT and next generation IACT [15], highlights that within the overlapping energy region between such instruments, it is the temporal domain of the next generation instruments in which the discovery frontier lies.

To pursue an exploitation of H.E.S.S. II in this direction, for the catching of new transients, a rapid repointing system for the telescopes has been implemented. This system has been designed to respond as fast as possible, without human intervention, to targets of opportunity (ToOs).

With an expected fall-off in intensity of the gamma-ray flux from GRB observed following the prompt phase emission, motivation exists for rapid response follow-up observations of such bursts. A minimisation in the repointing time for these observations over the last few years has succeeded to reducing the average overall response time to a timescale of ∼few minutes. Upper limits for such a follow-up observation of GRB 140818B are shown in fig. 3.

Beyond the successes of this H.E.S.S. II rapid response GRB ToO activity, efforts are also underway within collaboration to utilise H.E.S.S. II to catch other extragalactic VHE gamma-ray emitting phenomena. Specifically, attention is here drawn to the VHE neutrino and FRB follow-up observations carried out by the collaboration. With the origins of both these phenomena remaining
unclear, though believed in both cases to be (in part) extragalactic in origin, great potential exists for fresh insight about the emission mechanism to be provided by such follow-ups.

In particular, for the case of VHE neutrino follow-up observations, a strong potential link exists between high-energy neutrinos and gamma rays through the possibility that both particles are secondary losses of high energy cosmic rays within the region in or around their acceleration site. Provided that both particles types are able to escape from the source region and arrive to Earth, and the transient event overlaps sufficiently with the observation window, a detectable flux level is expected within the H.E.S.S. energy range.

An example of the recent improvement in response time to neutrino alerts is the follow-up observations of the ANTARES neutrino event on the 30th January 2017. These observations took placed only 32 seconds after the reconstructed neutrino event occurred. Although searches for a gamma-ray counterpart within this data set are still ongoing, the success of the automatic response system has already proved itself through this considerable reduction in the follow-up delay time to neutrino event alerts.

3. Intrinsic AGN Spectra

In parallel with efforts to broaden and deepen the range of sources detected in the H.E.S.S. II era, investigations are also being made to consolidate what lessons have been learnt from the detection of blazars in the H.E.S.S. I era. Specifically, this has been focused on their intrinsic spectral properties in this energy range.

The ability to accurately reconstruct the intrinsic spectra of blazars has two limiting factors. The first of these is dictated by the instrument sensitivity, which dictates the photon statistics obtained during observational campaigns of an object. The second of the constraints comes from the
limit in our understanding of the EBL, which at present is predominantly inferred a mixture of modeling [19] and VHE blazar observations [18].

Following the adoption of the recent EBL model and its associated uncertainty archival H.E.S.S. I data has been recently reviewed. An investigation was carried out to collectively infer what the full H.E.S.S. I data set revealed about the intrinsic AGN spectra. In particular, following the assumption that the intrinsic spectra are describable by power-law or log-parabola functions, the constraints on the free-parameters of these functions were obtained. Among other things, the results demonstrated the fact that only the brightest AGN flares, for which the highest statistics were obtained, showed a preference for log-parabola type spectra. The majority of AGN spectra, however, found no statistical preference for such a spectra, preferring instead the simpler power-law model.

4. Conclusion

The present epoch of H.E.S.S. extragalactic observations is one of a maturing and broadening frontier. Although an increase in the number of BL Lac blazar sources detected continues, there has also been an evolution of focus. This evolution is primarily thanks to recent improvements in the instrumentation which have lowered the energy threshold. Hand in hand with these instrumental improvements is the implementation of wide field-of-view monitoring and trigger follow-up schemes, allowing efficient capture of bright VHE emission follow-up observations.

AGN blazar variability is a well known and familiar phenomena. Despite this, however, the short-time variability results observed from recent FSRQ outbursts at VHE are challenging. An example case in point is the blazar 3C 279, which underwent a giant outburst in June 2015, demonstrated minute-scale variability at GeV energies. Such short-time variability at gamma-ray energies approaches the shortest level caught from the BL Lac PKS 2155-304. Since considerable internal absorption for FSRQs are expected should the emission zone be located within the BLR, both the compactness of the emission zone suggested by the short time-scale structure, and the large distance from the BLR region, are collectively rather challenging to reconcile.

Beyond new and deeper AGN observations, the new H.E.S.S. II era offers the promise for the discovery of new extragalactic VHE sources. Of particular relevance in this domain is the need for rapidly response to ToOs. The successful implementation of an automatic rapid response system is here demonstrated through the some of the first results obtained with this system.

Hand in hand with efforts looking to the future to explore the new range of phenomena open to H.E.S.S. II, the lessons learnt from H.E.S.S. I are considered. Looking back at the archival set of H.E.S.S. I AGN data, a clear message about what can be learned about the intrinsic spectra is found. The key message here being that only in brightest of AGN observations could the higher moments of the intrinsic spectra be probed.

In summary, exciting and increasingly challenging new results have arisen in the maturing discipline of H.E.S.S. AGN observations. The achievement of these results have come about both through the lowering of the instrument threshold allowing the detection of bright FSRQ flares, and the utilisation of wide field-of-view VHE AGN monitoring systems ensuring efficient follow-up observations of bright flares. These developments collectively ensure that this observational frontier continues to both broaden and deepen our understanding of extragalactic sources, fundamentally providing key insights into how these effective particle accelerators operate.
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