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Active galactic nuclei horizons from the gamma-ray perspective

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ABSTRACT

Recent results in the field of high energy active galactic nuclei (AGN) astrophysics, benefiting from improvements to gamma-ray instruments and observational strategies, have revealed a surprising wealth of unexpected phenomena. These developments have been brought about both through observational efforts to discover new very high energy gamma-ray emitters, as well as from further in-depth observations of previously detected and well studied objects. I here focus specifically on the discovery of repeated temporal structures observed in AGN lightcurves, and new hard spectral components within the spectral energy distributions of other AGN systems. The challenges that these new features place on the modeling of the sources are highlighted, along with some reflections on what these results tell us about the underlying nature of the emission processes at play.

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1. Introduction

The past several decades have seen extragalactic high energy γ-ray astronomy develop from an emerging discipline into a fully fledged research field. Starting in the 1990s with the first AGN discoveries of Mrk 421 and Mrk 501 (Punch et al., 1992; Quinn et al., 1996), the field now boasts of more than 60 AGN having been detected at very high energies (VHE) by ground-based gamma-ray instruments [1]. Following these observational achievements, a considerable array of different AGN subclasses, believed to represent various manifestations of a single (few) AGN type(s) (Urry and Padovani, 1995), are now identified. These range from the bright beamed blazars of both BL Lac and flat spectrum radio quasar (FSRQ) type, the most numerously observed AGN subclass at VHE, to their dimmer weakly beamed counterparts, radio galaxies.

The radio galaxy members of the AGN family observed at VHE, although much dimmer, offer the potential to provide direct spatial information about their emission site due to their locality. Contrary and perhaps complementary to this, the jet-beamed blazar family members, are observed as point-like sources. For these, information about the spatial extent of the emission site may instead 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 (The HESS collaboration, 2007) 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.

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[1] See http://tevcat.uchicago.edu for an up-to-date list.

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At present, three principal stereoscopic Cherenkov telescope instruments are currently in operation, H.E.S.S. based in Namibia, MAGIC based on the Spanish island of La Palma, and VERITAS based in Arizona in the USA. These sensitive stereoscopic Cherenkov telescope instruments collectively cover both the northern and southern hemisphere regions of the sky. Together, the achievements of these these instruments have brought about the present flourishing status of the field. Furthermore, an upgrade of each of them carried out around 2012, has resulted in significant improvements in their sensitivities, and a lowering of their threshold energies (Holler et al., 2016; D. B. Kieda for the VERITAS Collaboration, 2014; Sitarek et al., 2016).

Recent years have also seen the arrival of new monitoring instruments, with FACT (The FACT collaboration, 2015), and the now completed HAWC-300 (Pretz and for the HAWC Collaboration, 2016), 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 the maximum to be obtained from the present generation of instruments before the arrival of the next generation CTA north and south instruments (Actis et al., 2011).

In the following, several of the key recent observational developments in AGN gamma-ray astrophysics will be covered. In Section 2 the highest redshift AGN observed to-date will be focused on. Following this, in Section 3 the recently discovered first gamma-ray lensed AGN system will be discussed. In Section 4 the recent evidence for quasi-periodicity in a gamma-ray bright AGN will be highlighted. In Section 5, fast variability in FRSQ systems will be addressed. Lastly, in Section 6 the discovery of new unexpected spectral hardening features in local AGN will be covered. The conclusions to this discourse will be provided in Section 7.

2. High redshift AGN

At VHE, the propagation of photons is attenuated by the extragalactic background light (EBL) through pair production interactions. The strong energy dependence of this process, brought about by the required threshold energy for pair production, results in extragalactic space becoming optically thick $\tau > 2$ at redshift $z = 0.5$ (2) at for photon energies of 300 GeV (100 GeV) (Franceschini et al., 2008). It is therefore apparent that the threshold energy for an air Cherenkov telescope (ACT) instrument, has significant implications on the size of the Universe open to it for extragalactic observations.

The recent lowering of the threshold energy of ACTs to energies below 100 GeV, following upgrades back in 2012, has opened up the high redshift window to the Universe. Prior to these upgrades, the highest redshift AGN observed by ACTs had been 3C 279 (The MAGIC collaboration, 2008) (z =0.54), KUV 00311-1938 (Becherini et al., 2012) ($z > 0.51$) and PKS 1424+240 (Acciari et al., 2010) (z =0.60). Furthermore, with bright AGN, particularly FSRQ, whose outbursts are frequently brightest down at these energies, the opening up of the low energy domain allows for a rich ensemble of phenomena to be probed with the potential of high statistic results for bright outbursts.

Direct proof that access to the high redshift Universe has indeed been achieved through these upgrades of the instruments comes from the recent successful detection, both by MAGIC and VERITAS, of a flaring outburst from the FSRQ PKS 1441+25 in April 2015 (The VERITAS collaboration, 2015; The MAGIC collaboration, 2015). This AGN sits at a redshift of 0.94 (Shaw et al., 2012), making it the highest redshift VHE blazar detected to date. The spectral energy distributions (SED) obtained by the observations from these instruments, which both achieved threshold energies down well below 100 GeV, are both shown in Fig. 1. In this figure, the spectral values of both the observed, and EBL deabsorbed points are shown. Note the reference EBL model in the two plots are different, with the VERITAS SED adopting the model (Gilmore et al., 2012) and the MAGIC SED adopting the model (Domínguez et al., 2011). A comparison of the two observational result sets show striking agreement, validating both the detection and the robustness of the spectrum obtained by the two independent experiments.

Although remarkable simply for its high redshift value, the detection of this FSRQ at VHE brings with it additional new information. Perhaps one of the most striking such results, however, actually comes from what is not seen. The continuation of the spectral slope in the derived SED, particularly apparent through the comparison of the *Fermi*-LAT and deabsorbed VHE spectrum, amounts to a lack of evidence of internal absorption being present in the intrinsic spectrum output by the source. In turn, this result can be used to place strong constraints on the position of the emission site with respect to the broad line region location (Tavecchio and Ghisellini, 2012). With gamma-ray emission up to 200 GeV detected from this source, the emission site is found to be constrained to sit at a distance beyond $r_{\rm BLR} \approx 10^{17}\ {\rm cm}\left(L_{\rm disk}/10^{45}\ {\rm ergs}^{-1}\right)^{1/2}$ (Ghisellini and Tavecchio, 2009), where $L_{\rm disk}$ is the thermal luminosity of the accretion disk which is spectrally dominated by the output in the optical energy range. This point will be returned to later in Section 5.

The detection of this high redshift AGN, out at a redshift of 0.94, carries other implications related to the subsequent tranparency of space outside the source in the extragalactic environment, and the corresponding EBL constraint. The rule-of-thumb is that a VHE photon of energy E_γ, emitted by a source at redshift z, attenuates off background photon of wavelength λ such that, $(E_\gamma/{\rm TeV})/(1+z)^2 \approx (\lambda/\mu{\rm m})$. Following this guideline, the detection of VHE $<$ 100 GeV flux from a source at redshift $z \approx 1$ predominantly provides EBL information for the small wavelength component ($\sim 0.6\,\mu$m), as shown in left-hand panel of Fig. 2. Under the assumption that the intrinsic spectral shape follows a simple mathematical functional form, the constraints on the normalisation of a fiducial reference model, (Domínguez et al., 2011), are shown in the right-hand panel of Fig. 2.

These high redshift AGN observations clearly demonstrate the successful reduction in energy threshold of both MAGIC and VERITAS instruments. In a similar manner, the H.E.S.S. collaboration demonstrated the successful reduction of the H.E.S.S.-II energy threshold through the detection of the FSRQ 3C 279, at a redshift of $z \approx 0.54$, in a flaring state back in 2015 (Cerruti et al., 2017). The implications of these observations, which achieved an energy threshold of $\sim$ 66 GeV, will be discussed further in Section 5. This collective reduction in the energy threshold of the different ACT instruments, therefore, has quickly borne fruit.

3. Gravitationally lensed AGN

The recent upgrades of the stereoscopic ACT instruments which have opened up the high redshift window, have led to the discovery of an ensemble of new unexpected phenomena. One prime example is the detection of the first VHE gamma-ray gravitationally lensed system, B0218+357 (The MAGIC collaboration, 2015). Within this system, the source AGN sits at a redshift of $\sim$ 0.94 (Cohen et al., 2003), and the lens at a redshift of $z \approx$ 0.68 (Browne et al., 1993).

This system was detected several years ago at GeV gamma-ray energies by the *Fermi*-LAT satellite (The Fermi collaboration, 2014). Since then, the lensed AGN has exhibited several GeV bright flaring episodes, along with the subsequent detection of their corresponding delayed counterparts (see top-panel of Fig. 3). The delay times between these flares and their counterparts have been repeatedly

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