Astro2020 Science White Paper

Surveying TeV Gamma-ray Emission from Active Galactic Nuclei

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☑Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☑Multi-Messenger Astronomy and Astrophysics

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Abstract: Very-high-energy gamma-ray photons (≥100 GeV) are expected from blazars and some radio galaxies, special sub-classes of active galactic nuclei (AGNs). These gamma-ray photons can provide crucial information of fundamental physics around the intergalactic magnetic field, the radiative processes and acceleration mechanisms, multi-wavelength and multi-messenger observations, periodicity, and beyond-the-Standard-Model physics. A wide field-of-view TeV gamma-ray observatory with a large duty cycle will be one of the best gamma-ray instruments to study AGN phenomena at very-high energies. The majority of the material is drawn from *Science Case for a Wide Field-of-View Very-High-Energy Gamma-Ray Observatory in the Southern Hemisphere* [1]. If you would like to cite results presented in this white paper, please cite the original paper.

1 Introduction

Active galactic nuclei (AGNs) are one of the most luminous astrophysical objects in the Universe. Most of these sources are powered by accretion onto a supermassive black hole (SMBH) [2] leading to collimated relativistic ejecta that transport plasma with high Doppler factors [3]. AGNs present unique observational signatures that include very high luminosities and short variability time scales over the entire electromagnetic spectrum. Their broadband spectra, ranging from radio wavelengths to very-high-energy (VHE; $\geq 100\,\mathrm{GeV}$) gamma-rays, are extensively studied through multi-wavelength campaigns. The dominant population of AGNs detected at very-high energies are blazars[1], followed by Radio galaxies [4, 5, 6, 7]. At VHE emission, blazars show rapid variability and exhibit non-thermal spectra which indicate that the observed emission originates inside the highly relativistic jets aligned near the observer's line of sight. Radio galaxies display giant lobes and large-scale off-axis jets with large viewing angles. The spectral energy distributions (SED) of blazars have double-peak structures which are usually explained by the non-thermal synchrotron self-Compton (SSC) model [8, 9, 10], although hadronic models have been required for some blazars [11, 12, 13, 14, 15]. The low-energy peak, from optical to X-rays, is attributed to synchrotron radiation from relativistic electrons while the high-energy peak is believed to be due to SSC emission [16] and/or hadronic synchrotron-proton blazar processes [11, 17]. The SSC emission is produced through the scattering by relativistic electrons of the self-produced synchrotron photons [16]; and the hadronic emission is explained mainly through the contribution of charged and neutral pion decay products [11, 17]. Depending on the location of the synchrotron peak in the SED, BL Lac objects (a type of blazar) are classified [18] into low-energy peaked BL Lac (LBL), intermediate-energy peaked BL Lac (IBL), the dominating sub-class (~ 50), high-energy peaked BL Lac (HBL) and the smallest, most extreme sub-class, the high-energy peaked BL Lac (EHBLs).

2 Extreme high-energy peaked BL Lacs

In recent years, increasing attention has been put on a sub-class of blazars known as extreme high-energy peaked BL Lacs, for which the low-energy peak is located at energies ≥ 1 keV [19] and the high-energy peak at energies ≥ 1 TeV [20].
The description of their broadband SED in the framework of the SSC model suggests an atypically low magnetic field ($\mathrm{B} < 10^{-2}\,\mathrm{G}$) [21] and a large minimum electron Lorentz factor ($\gamma_e \sim 10^5$) [22, 23]. In the hadronic scenario, proton-synchrotron emission and secondary cascades inside the emitting region initiated by ultrarelativistic hadrons have been invoked [24]. The study of jet phenomenology, together with ultra-high-energy cosmic ray astrophysics, make these objects very interesting. At large distances ($z > 0.3$), the photon-photon absorption by the extragalactic background light (EBL) becomes strong. These observations are therefore also particularly interesting for studies about radiative processes, acceleration mechanisms, the intergalactic magnetic field, and searches for

[1] http://tevcat.uchicago.edu/

physics beyond the Standard Model, such as axion-like particles or Lorentz invariance violation [25].

3 Multi-wavelength and Multi-Messenger Observations

3.1 Multi-wavelength Observations

Markarian 421 (Mrk 421) has been a frequent target of multi-wavelength campaigns, to study correlations among distinct energy bands and optical polarimetric observations. The multi-wavelength (from radio to TeV bands) campaign performed between January 19, 2009 to June 01, 2009 provided an excellent energy coverage which allowed the broadband SED of Mrk 421 to be studied in quiescent state. It could be explained in the framework of a one-zone SSC model with three power-law functions (i.e., two breaks) and a hadronic model through Synchrotron Proton Blazar [26]. On the other hand, Mrk 421 exhibited the strongest flaring activity in almost all energy band during 2013. The multi-wavelength light curves including polarization degree and position angle variations from January 02, 2013 to July 27, 2013 are presented in Figure 1 (left-hand panel). This strong flare was widely monitored in several energy bands and was observed from 2013 April 09 to 19 in TeV [27], GeV [28], hard/soft X-ray [29, 30, 31], and optical [32, 33] bands. It is presented in three episodes. During the first episode, Mrk 421 exhibited the largest activity in TeV, X-ray, and optical bands. The TeV gamma-ray and optical fluxes were found to be anti-correlated, and the polarization degree and the position angle were found to be correlated. During the second episode, a long rotation of the position angle of $\sim 100^\circ$ with a degree of polarization of $\sim 2\%$ was observed. This result might be evidence for the shocks traveling along helical magnetic field lines [34]. The TeV gamma rays and X-ray flaring activities were accompanied by a moderate increase in the optical band. The optical flux was found to be strongly correlated with the position angle and anti-correlated with the polarization degree. In addition, a strong anti-correlation between the position angle and polarization degree was exhibited. During the third episode, a maximum value of the polarization degree of $\sim 8.33\,\%$ was observed when TeV, X-ray, and optical fluxes were decreasing. No correlations were displayed among the optical flux with the rest of the higher energy emission. The normalized Stokes parameters q and u exhibited a strong correlation, thus indicating that the variability was due to a single variable component with constant polarization properties [35]. Nothing relevant can be concluded about the flare in May due to lack of TeV observations. Due to its large field-of-view and duty cycle, the next generation of a wide field-of-view TeV gamma-ray observatory will be the only instrument to provide these unbiased, quasi-continuous light curves.
Mrk 421 went into a long-lasting outburst phase starting on July 09, 2012 and ending on September 17, 2012 when this object was unreachable by optical telescopes. Only some instruments, including ARGO-YBJ [36], *Fermi* [37], BAT, NuSTAR [38] and OVRO [39] could observe this outburst. Although the *Fermi* collaboration reported the highest flux observed by this source since the beginning of the *Fermi* mission [37], ground-based instruments such as Imaging Atmospheric Cherenkov Telescopes (IACTs) could not detect

it. Simultaneity of the multi-wavelength and polarimetric observations, along with unbiased monitoring, play a key role in understanding the radiative processes and acceleration mechanisms associated with AGNs.

3.2 Multi-Messenger Observations

High-energy neutrinos provide a crucial piece of information in the quest for the sources of high-energy cosmic ray accelerators as they evidence interactions of energetic hadronic particles. Significant experimental efforts over the last decades have been crowned by the detection of an astrophysical flux of high-energy neutrinos by the IceCube collaboration [40].

A very promising way to achieve the goal of localizing high-energy neutrino and thus cosmic rays sources is the multi-messenger approach: combining the advantages of high-energy gamma-ray observations (i.e. precise localization of the emission region allowing for the identification of the astrophysical source, study of the overall energetic sources and the energy and time dependent power output, etc.) with the link to hadronic origin of the radiation brought by high-energy neutrino observations.

First attempts were made with the Neutrino Target of Opportunity and Gamma-ray Follow-Up programs, involving IceCube, MAGIC, and VERITAS [41, 42]. Also searches for persistent gamma-ray emitters in the error box of individual high-energy neutrinos [43, 44, 45] were performed. All major high-energy neutrino telescopes have now implemented and commissioned automatic data analyses and alert systems able to inform the broader community within seconds about the detection of a promising neutrino candidate [46, 47]. Follow-up programs of these alerts have been installed with all current IACT collaborations [48] and similar plans are outlined for Cherenkov Telescope Array (CTA) [49].

The searches for transient high-energy gamma-ray emission correlated with high-energy neutrinos already revealed a first promising result: the detection of the flaring blazar TXS 0506+056 in coincidence with the high-energy neutrino event IceCube-170922A [50]. The significance of the temporal and spatial correlation between the neutrino event and the blazar, which at the time was flaring in high-energy gamma rays, is estimated to be at the 3σ level. The analysis of archival data from IceCube revealed an increase in the rate of neutrino events from the direction of TXS 0506+056 over the course of period of about 100 days in 2014–2015 [51], providing further evidence that TXS 0506+056 is a potential neutrino source. An overview over the multi-wavelength observations of TXS 0506+056 and their relation to the neutrino data is given in Figure 1. This first evidence of a multi-messenger signal involving high-energy neutrinos opened a new window to the violent universe and illustrates one of the likely paths to resolving the century old quest for the sources of cosmic rays.

On the other hand, this first event also raised many new questions and the need for follow-up studies and confirmations that can only be brought about by a next generation wide field-of-view TeV Observatory, like a Southern Gamma-ray Survey Observatory (SGSO) [1]. Crucial is the need of long-term light-curves of blazars at the highest energies. This is illustrated further by the low sensitivity of VHE gamma-ray observations of TXS 0506+056 during the 2014–2015 outburst, that could help to constrain the high-energy

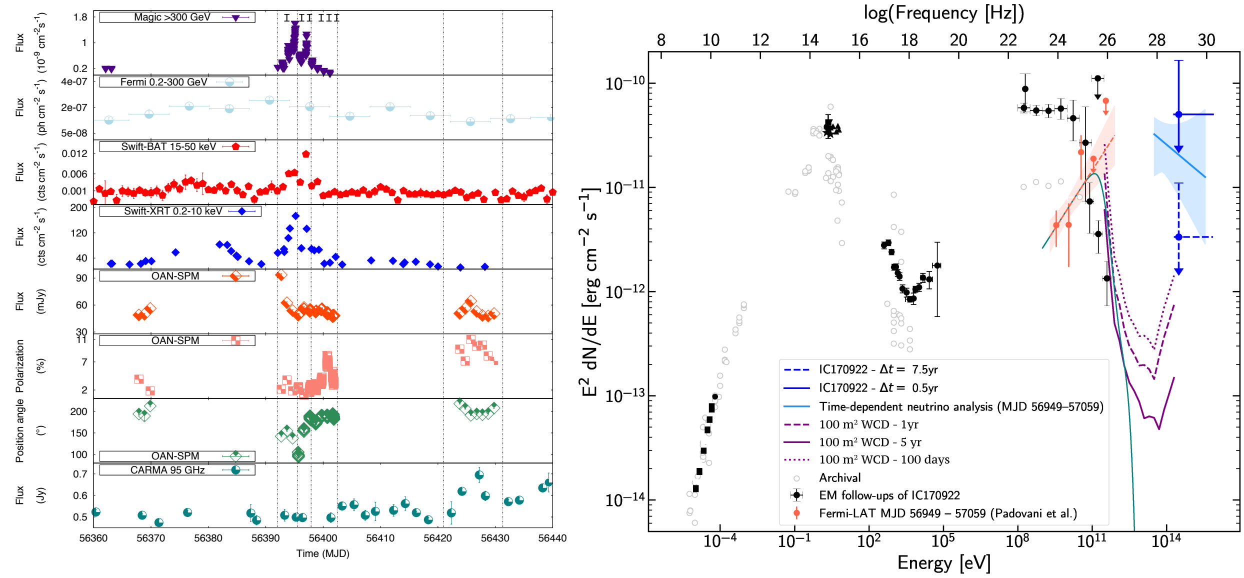

Figure 1: Multi-wavelength and multi-messenger observations of TXS 0506+056 illustrating the crucial energy and sensitivity range a 100k m^2 WCD will cover. Modified from [50, 51].

emission of the source. A next generation wide field-of-view TeV Observatory [1] will be a unique instrument to provide these unbiased, quasi-continuous light curves for blazars in the Southern sky. Statistical analysis of light-curves will allow the derivation of the frequency of occurrence of blazar flares in the TeV energy range, a crucial input to evaluate the significance of neutrino-blazar flare correlations. This is currently not available in the VHE regime. In addition, only a TeV observatory will monitor sources that are spatially consistent with the neutrino direction over a wide range of time scales.
The MeV–GeV flare of TXS 0506+056 detected by *Fermi*-LAT lasted for several months, but the source was detected above a 100 GeV only 11 days after the neutrino [52]. H.E.S.S. observations taken 4h after the neutrino detection did not reveal significant gamma-ray emission [53]; only an extensive campaign over two weeks following the neutrino event allowed the detection of TXS 0506+056 by MAGIC [52], and over a few months for VERITAS [54]. While these extensive campaigns allowed to detect variability at the timescale of days [52], the necessary observation/monitoring time will be difficult to obtain for a large number of follow-up observations. A higher energy threshold compared to IACTs will be needed to search for high-energy gamma rays associated to any neutrino alert falling into its field-of-view. Such an observatory will be the only instrument able to detect gamma-ray emission at any timescale surrounding the arrival time of neutrino events and will thus be able to provide an unbiased assessment of the correlation between messengers.

4 Blazar Periodicity

The typical radiation observed from blazars appears to be stochastic and unpredictable. However, in the optical band, periodicity has been claimed with a period of 12 years from OJ 287 [55], and with a period of 16 years from Mrk 421 [56]. At present, due to observational gaps and incomplete data samples, no unambiguous periodicity has been observed from blazars in the gamma-ray bands, although some studies have found hints of periodicity in the VHE emission from Mrk 501 [57, 58] and the GeV emission from PG 1553+113 [59]. Periodic emission could be expected, for instance, if the central objects powering the AGNs were binary systems of black holes [60]. Long-term observations are essential for disentangling deterministic and stochastic processes, especially on time scales of months to years. Only an unbiased monitoring instrument such as the next generation of a wide field-of-view TeV gamma-ray observatory will be able convincingly to demonstrate the presence of periodic components on these time scales in the VHE emission from blazars.

4.1 Measuring the IGMF

Blazars can also be used to measure or limit the strength of the intergalactic magnetic field (IGMF) presumed to exist in the voids of the large scale structure. Since the IGMF is likely formed from processes occurring during phase transitions in the early universe, its detection and characterization would serve as a probe of the universe prior to the formation of the Cosmic Microwave Background (CMB) [61]. Measurements of the IGMF based on VHE gamma-ray observations typically rely on the development of intergalactic cascades initiated by pair production interactions of VHE gamma rays with the EBL and continuing via the subsequent up-scattering of CMB photons into the high-energy or VHE bands [62, 63]. Recent efforts (e.g., [64, 65, 66, 67, 68, 69]) based on the non-observation of the cascade emission place a lower limits on the IGMF strength on the order of 10^{-16} to 10^{-14} Gauss. However, these constraints rely on assuming that the VHE observations, frequently taken over a few to several tens of hours, represent the average flux from the source on the time scale T over which the cascade develops, which can be approximated by [70]

$$T \approx (2 \text{ years}) \left(\frac{E_\gamma}{100 \text{ GeV}}\right)^{-5/2} \left(\frac{B_{\text{IGMF}}}{10^{-17} \text{ Gauss}}\right)^2, \quad (1)$$

where E_γ is the observed gamma-ray energy and B_{IGMF} is the strength of the IGMF. The next generation of a wide field-of-view TeV gamma-ray observatory will perform unbiased monitoring of sources used for these IGMF studies, checking this assumption on time scales of 5 to 10 years. These observations will be a crucial component in assessing the robustness of IGMF limits placed by previous IACTs, as well as by CTA in the future.

5 Conclusions

VHE monitoring observatories follow playing an important role in our understanding of the intergalactic magnetic field, the radiative processes and acceleration mechanisms in EHBLs, the multi-wavelength and multi-messenger observations, periodicity, and beyond-the-Standard-Model physics such as axion-like particles or Lorentz invariance violation. In particular, a wide field-of-view TeV gamma-ray observatory would be capable of detecting several known VHE blazars at distinct time scales. Combined with its ability to monitor in an unbiased way over the full Southern sky, this kind of observatories will uniquely contribute to extragalactic VHE science.

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