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Unbiased Long-Term Monitoring at TeV Energies

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Abstract: For the understanding of the variable, transient and non-thermal universe, unbiased long-term monitoring is crucial. To constrain the emission mechanisms at the highest energies, it is important to characterize the very high energy emission and its correlation with observations at other wavelengths. At very high energies, only a limited number of instruments is available. This article reviews the current status of monitoring of the extra-galactic sky at TeV energies.

Keywords: monitoring; very high energies (VHE); TeV energies

1. Unbiased Monitoring

The non-thermal universe is highly variable. In particular, the extra-galactic sky is dominated by variable objects such as active galactic nuclei (AGNs) and transient objects such as gamma-ray bursts (GRBs). Whatever the type of source, the variety in morphology of light curves and energy spectra has impeded their complete understanding. Even more, the redshift at which these sources are detected is limited by attenuation of gamma rays at the highest energies by the extra-galactic background light (EBL). For instance, in the case of GRBs, this limitation will decrease the number of detected events. Unbiased monitoring increases the exposure and therefore the sampling of extra-galactic sources and/or their variable activity. With this, alerts triggering interesting multi-wavelength and multi-messenger studies are allowed. Furthermore, all-sky monitoring enables population studies and discovery of new sources.

1.1. Active Galactic Nuclei

More than half of the gamma-ray sources emitting at GeV energies are AGNs [1], of which more than 35% are blazars. Among the TeV sources, about 40% are AGN and more than 20% are high frequency peaked BL Lac type objects (HBLs) [2]. Blazars are extremely variable objects across a wide range of wavelengths, on time scales from minutes (e.g., PKS 2155-304 [3], Mrk 501 ([4]) to years [5]. Their spectral energy distribution spans from radio to TeV energies and shows a double-peak structure [6]. The low-energy peak originates in leptonic synchrotron radiation [7], while the origin of the high-energy peak is still under debate (e.g., synchrotron self-Compton (SSC), external Compton (EC) or hadronic [8,9]). To understand where the high energy emission is coming from and whether the underlying acceleration processes are Fermi-acceleration [10], magnetic re-connection [11–14] or stochastic acceleration of cosmic rays [15]; whether the radiation processes are of leptonic or hadronic origin; and whether AGNs are cosmic ray accelerators, TeV monitoring is crucial. For instance, monitoring allows unbiased studies of light curves and their flux distributions. An unbiased light curve covering several years can uncover periodicity, the maximum available power of the central engine, the source's duty cycle and, if it exists, their steady state. Studying the shape of flux distributions allows for conclusions on the type of the underlying physics processes [4], either multiplicative or additive. Analyzing the power spectrum and properties of bright flares, the variability time scale can be constrained. This allows for conclusions on the size and location of the emission region.

1.2. Transients

The extra-galactic transient sky is dominated by the most luminous phenomena, Gamma-ray Bursts (GRBs). Nearly ten thousand have been detected thus far. These non-repeating gamma-ray flashes are likely to be associated to the final phases of the life of massive stars when its duration is longer than two seconds or to mergers of compact objects otherwise. The initial or prompt gamma-ray emission is followed by a late and delayed emission, called afterglow, from radio to high-energy gamma-rays. In particular, high-energy emission for more than 130 bursts has been observed [16] by the Large Area Telescope instrument on board the Fermi satellite (Fermi-LAT). Interestingly, for several bursts, such a high-energy component is not consistent with an extrapolation of the prompt component. They even show a different spectral evolution and a temporal offset, and they are longer lasting when compared to the prompt phase. Because of these characteristics, this behaviour is generally correlated to the X-ray afterglow [17] and understood as synchrotron external-shock emission. However, observations of photons with energies above 10 GeV for long [18–20] and short [21] GRBs disagree with this interpretation.

Gamma-ray emission above 10 GeV is expected from leptonic and hadronic models. Several attempts have been carried out to observe TeV counterparts, despite the challenge imposed by the EBL absorption. Since the possible TeV emission associated with GRB 970217A detected by the Milagrito experiment, only the MAGIC experiment has reported a hint of a signal above 400 GeV from GRB 160821B [22] and the recent detection of GRB 190114C above 300 GeV [23]. As the challenge for pointed instruments is the short duration of GRBs, e.g., in the case of MAGIC, a special telescope design has been chosen to allow for fast repositioning [24]. Monitoring instruments with a large FoV overcome these limitations.

Fast Radio Bursts (FRBs) are sources discovered in the last decade. Over 60 FRBs have been observed [25] in radio wavelengths with a duration of only milliseconds. Their origin is unknown but considered to be extra-galactic with redshifts below one. They share similarities to sources (as GRBs) and their short redshifts have inspired follow-up campaigns to search for TeV counterparts with no positive detection up to now. FRBs are an excellent example of the astronomical surprises that the transient extra-galactic sky is offering to us.

2. Gamma-Ray Astronomy at TeV Energies

Direct observation of gamma rays can be done only in space. However, limited by the detector volume, gamma-ray satellites have their best performance in the low-energy gamma-ray regime from MeV to GeV. Fortunately, there are indirect measurement techniques that allow for observations on ground at higher energies. This section gives an overview on the techniques and the instruments dedicated to observed the TeV sky.

All techniques are based on pair-creation. In satellites, this happens within the detector on-board. Ground-based instruments on the other hand have the atmosphere as part of the detector. Here, gamma rays interact with the atmosphere and initiate particle cascades. Ground based instruments either detect those particles or the Cherenkov light emitted during their path in the atmosphere. The different techniques are discussed in the context of monitoring.Currently, the Agile and Fermi satellites are scanning the sky in gamma rays. Large field of views (FoVs) and continuous scanning of the whole sky are ideal for monitoring the transient sky. A detailed review of the monitoring results of the Fermi satellite is given in this special issue [26].

2.1. Imaging Air Cherenkov

Imaging air Cherenkov telescopes (IACTs) observe the Cherenkov light emitted from extensive air showers in the atmosphere. IACTs are pointed instruments with a typical FoV between 3° and 5°. This technique was pioneered by the Whipple 10-m telescope, which detected the first source at very high energies (VHE) [27]. The second generation of IACTs discovered in the order of 10 VHE sources. With the goal to close the gap to the satellite measurements, the third generation of IACTs aimed for better sensitivity and lower energy threshold. With a sensitivity of about 1% of the flux of the Crab Nebula, these instruments could increase the number of VHE sources to more than 200. In the Northern Hemisphere, there are the IACT arrays of the two MAGIC telescopes in La Palma and the four VERITAS telescopes in Arizona. In the Southern Hemisphere, the H.E.S.S. array consisting of four medium size and one large telescope observes at VHE. With the excellent sensitivity, these instruments have to cover a variety of physics cases, limiting the time available for monitoring. Therefore, the First G-APD Cherenkov Telescope (FACT) was built to monitor a small sample of sources with high cadence. With a smaller mirror area of only 9.51 sqm, FACT has a higher energy threshold than the large IACTs. While the sensitivity of IACTs is a large advantage, the pointed observations and the optical detection principle limit their duty cycle.

2.2. Water-Cherenkov

The water-Cherenkov technique is based on the direct measurement of relativistic particles in extensive air showers initiated by gamma rays. To measure the shower front, water-Cherenkov instruments have to cover a large area. Their main element is water, in which Cherenkov light is produced by the relativistic particles. These instruments have the advantage of having a large field of view (FoV) of $2\pi\cdot$sr to observe the TeV sky 24/7 up to energies as high as 100 TeV. Among their main strengths is the capability to perform all-sky surveys, to discover extended sources, detect the highest-energy accelerators and to monitor the sky for TeV transient and variable sources. The water-Cherenkov technique was pioneered by the Milagro experiment that achieved the first detection of the TeV gamma-ray emission from the Galactic plane [28] and its spatial distribution [29]. It also discovered TeV sources in the Galactic plane [30]. The next generation of water-Cherenkov instruments added the high altitude to achieve an improvement in the sensitivity of a factor of ten. Currently, the High Altitude Water Cherenkov (HAWC) gamma-ray observatory is using this technique.

2.3. Others

Apart from that, also non-imaging Cherenkov arrays are used, for which non-pixelized detectors are spread over a wide area. Their data are interpreted using the timing of the Cherenkov light arriving in the array of Cherenkov light detectors. Some experiments such as Taiga and LHAASO use several measurement techniques to combine the information in the analysis.

3. Observations at Very High Energies

Both type of instruments, with large and small FoV, are used for monitoring. Especially for extremely variable sources such as blazars, a variety of monitoring programs are available. For other transient objects such as GRBs, the triggers are delivered by wide FoV instruments and pointed telescopes perform follow-up observations of alerts.

3.1. Monitoring Campaigns

Limited in sensitivity, the first and second generations of IACTs observed a relatively small sample of sources although collecting a lot of data. Results by the telescopes of the second and third generation have been collected in [31]. Until 2009, the Whipple 10-m continued its operation to perform monitoring of the brightest blazars. The long-term observations of Mrk 421 are summarized in [5].

Since 2009, MWL monitoring has been organized each year [32]. However, the large IACTs have a limited capacity for monitoring, as they have to cover a variety of other physics cases and sources as well. Therefore, the observation time dedicated to monitoring is limited to about 100–250 h per year, which is shared among several sources. The fraction of observations dedicated to AGNs is larger. For example, VERITAS has dedicated nearly 5000 h of observations time on AGN [33]. However, the observations to detect new sources and study AGN flares are naturally biased towards higher fluxes. Many of the AGN observations, especially new detections, are triggered by other wavelengths [34] based on an enhanced flux state in these wavelengths. In addition, for the bright sources, a lot of observation time is spent on the follow up of alerts [32], in many cases also from self-triggers.

3.2. FACT

To avoid any bias from triggered observations, the First G-APD Cherenkov Telescope (FACT) [35] is monitoring a small sample of sources [36]. Dorner et al. [37] compared the monitoring of the large IACTs with the dedicated monitoring program of FACT. Using silicon-based photo-sensors, the telescope is ideally suited for long-term monitoring. These photo-sensors have an excellent long-term stability and performance improving the sensitivity. A stable performance with time and observing conditions is very useful in the context of long-term observations. In addition, the fact that the gain of silicon-based photo-sensors does not degrade when they are exposed to bright light, is very useful in the context of monitoring, as it allows maximizing the duty cycle of the instrument and minimizing the observational gaps around full moon. Similarly, the efficiency of the instrument has been increased to more than 90% yielding up to 2500 h of physics data per year. In total, FACT has been observing for more than 13,500 h. On individual sources, up to 3000 h of physics data have been collected providing an unprecedented data sample. This data sample allows studying the underlying physics processes [4], search for periodicity [38] and study characteristics such as steady state emission and duty cycle.

To foster MWL and ToO observations, FACT has an automatic quick-look analysis [39]. The results are available on an open-access website[1] with low latency. Based on this analysis, a variety of alerts are sent. Via a memorandum of understanding (MoU) with other gamma-ray instruments, alerts on blazar flares are exchanged. FACT also sends these alerts to the multi-messenger network AMON [40] and target-of-opportunity programs have been set up with X-ray satellites [41]. In total, nearly 90 alerts have been sent in the last five years and nine astronomer's telegrams have been issued.

3.3. HAWC

While FACT does pointed observations and is limited by night-time observations, the High Altitude Water Cherenkov (HAWC) observatory is using the water-Cherenkov technique, which allows for 24/7 monitoring without gaps due to sun or bad weather. Every day, HAWC scans 2/3 of the sky. The allsky-map with data from the first 507 days of operations [42] shows over 39 sources, which added 19 as new sources to the TeV catalog, some of them being extended. The most interesting sources in this catalogue, with a dedicated publication [43], are the PWNs Geminga and PSR B0656+14. Studies of their morphology constrain the diffusion of particles away from them and show that they are unlikely the origin of the positron excess, first observed by the PAMELA detector [44]. HAWC also reported [45] TeV gamma-ray emission from the micro-quasar SS433 spatially coincident with its lobes.

In the extra-galactic sky, the brightest sources seen by HAWC are Mrk 421 and Mrk 501. To alert other instruments, three monitoring programs are available. One of them is the all-sky monitoring program, a self-triggered search in sliding time windows as short as 0.2 s up to a few transits. This program is most sensitive to search for GRBs at TeV energies, gravitational wave follow ups [46] and any other unknown transient. A second program [47] is dedicated to known GeV and TeV sources. It searches for TeV emission in time scales of minutes to hours, in particular for bright flares

[1] https://fact-project.org/monitoring/

of Mrk 421 and Mrk 501. A third program is dedicated to the follow up of external alerts from MoU partners (VERITAS, MAGIC, H.E.S.S., FACT, Fermi, IceCube, LIGO/VIRGO, AMON, SWIFT, NuStar and Antares) with fixed sky positions and on time scales of 1, 20 and 100 s. This program is mostly dedicated to GRB follow ups. Besides the monitoring programs, an analysis of light curves including all HAWC data is performed to identify ties of similar activity with a Bayesian Block analysis [48] and periodicity in sources such as blazars, prompt [49], long lasting or delayed emission in GRBs [50] and neutrino [51,52]; and gravitational wave counterparts [53].

More interesting results are to come from analyses being developed towards the catalogue of sources of the highest-energy gamma rays and a third source catalogue including more than four years of data.

3.4. Combined Observations

While water-Cherenkov instruments have a better duty cycle and more continuous coverage, IACTs provide a better sensitivity. FACT and HAWC observations have been combined already providing a 12 h coverage in time [53,54]. Furthermore, FACT follows up alerts from the HAWC online search for hot-spots and flares in blazar light curves.

3.5. Future Instruments

For future monitoring, three approaches are pursued. They will provide complementary performance in the study of transient and variable sources, as discussed below.

One approach, led by the Cherenkov Telescope Array (CTA), is to use future large IACTs to follow up external alerts of transients events for a limited observation time. In addition, a reference sample of AGNs will be monitored for very small amount of observation time per source and with a very small cadence. The advantage of CTA is the unprecedented timing and spectral resolution, although the observations will be biased by external alerts and small time coverage when compared to other approaches.

The second approach is to extend the temporal coverage by placing small FACT-like telescopes around the globe [55] to monitor bright TeV sources (mainly blazars) with a larger time coverage, to send alerts to trigger multi-wavelength and multi-messenger observations. The main advantage is the large exposure per year of several hundreds of hours per source with reasonable time and spectral resolutions.

Monitoring at TeV Energies (M@TE) [56,57] is a project carried out by Mexican and German groups with the goal to install a FACT-like telescope in the observatory San Pedro Mártir, Baja California, Mexico to extend the monitoring performed by FACT to achieve a 12-h coverage per day. A large fraction of the hardware components have been acquired already. The mirrors have been characterized and the drive system assembled. Two mounts are available, one situated at the HAWC site and the second one will be installed in San Pedro Mártir. The mount at the HAWC site offers the possibility to cross-calibrate the water-Cherenkov and imaging air-Cherenkov techniques. Extending the coverage to 12-h placing the second mount in San Pedro Mártir will allow for a better assessment of the duration of flares. While it is known that the duration of many flares is in the order of one to a few days, only few measurements of the rising or decaying edge of the flares is available.

Finally, the third approach, led by the Southern Gamma-ray Survey Observatory (SGSO) [58] Alliance is to extend the sky coverage by building a wide-FoV detector in the Southern Hemisphere. SGSO is conceived as an array of detector units covering a large area and situated at high altitude but with better sensitivity than HAWC. SGSO inherits HAWC's strengths to perform all-sky surveys, to follow up external alerts and to generate alerts to other instruments. It will monitor the sky for TeV transient and variable sources with the largest temporal coverage at the highest energies.

The LHAASO instrument [59] combines most of the known techniques in gamma-ray astronomy: IACTs, water-Cherenkov and scintillator detectors. In terms of monitoring, its array of scintillator detectors and water-Cherenkov detectors will continue HAWC's efforts in the Northern Hemisphere with an improved sensitivity.

4. Multi-Wavelength and Multi-Messenger Context

Unprecedented achievements in the understanding of transient and variable sources have resulted from multi-wavelength and multi-messenger observations. For instance, the multi-wavelength campaign organized [8] by the Fermi-LAT team to observe Mrk 421 from radio to TeV, during 4.5 months, every second day, independently of the observation conditions and the level of activity of the source, results in the best description of the spectrum of Mrk 421 in a low state. It showed a wider than expected high-energy peak which description required more than one electron population in the SSC scenario. Simultaneity of the observations and an unbiased monitoring play a key role in the conclusions.

During 2016, a bright flaring activity over several weeks was observed from the source 1ES 1959+650. Thanks to the wealth of multi-wavelength and multi-messenger data, different studies could be carried out. Dorner et al. [60] used the X-ray data to predict the VHE gamma-ray flux. This shows that a simple SSC model cannot explain the observed VHE emission. On the other hand, Kintscher et al. [61] showed that no neutrino emission, as expected from hadronic models, is correlated with the flaring activity of 1ES 1959+650.

On the other hand, multi-messenger follow up of the high-energy neutrino IceCube-170922A [52] found the blazar TXS 0506+056 in coincidence with IceCube-170922A at a 3σ level and flaring in GeV gamma rays and X-rays. Moreover, archival data from IceCube observatory showed an increase of neutrino events from the direction of TXS 0506+056 over 100 day during 2014–2015 [52], increasing the evidence that TXS 0506+05 may be a neutrino source. Archival data from all-sky survey instruments as HAWC or monitoring programs dedicated to known AGNs, for at least the period of 2014–2015, would contribute important pieces to the puzzle. For instance, if TXS 0506+05 were found to have TeV emission, it would definitely strengthen the hypothesis of being a neutrino source.

There are also very good examples of multi-wavelength and multi-messenger observations impacting our understanding of transient sources as GRBs. For instance, the multi-wavelength observations of the bright, long gamma-ray burst GRB 110731A [20]. For the first time, simultaneous GeV, X-ray, and optical data were available over multiple epochs for a GRB allowing temporal and spectral analysis. Results favor emission from the forward shock in a wind-type medium, characteristic of massive stars when considered as progenitors of long GRBs.

One of the most striking results from multi-messenger observations of GRBs came from the IceCube observatory. It reported [62] no coincidences between neutrinos and GRBs after analyzing two years of data. This implies that there may be another source of cosmic rays with energies above 10^6 TeV. It is important to point out that this result involved an all-sky monitor gamma-ray instrument to detect as many GRBs as possible, as well as an all-sky monitor neutrino instrument to search for coincidences.

Multi-wavelength and multi-messenger observations are being carried out by present instruments. Automated procedures and alerts have been developed to achieve rapid communication between instrument as the Gamma-ray Coordinates Network (GCN), the Astrophysical Multi-messenger Observatory Network (AMON) [63] and the Whole Earth Blazar Telescope network[2] However, clearly, the most efficient way to get simultaneous and data previous to the alert is by having all-sky monitoring instruments in different wavelengths.

5. Conclusions

The current status of monitoring at TeV energies of the extra-galactic sky has been reviewed. In addition, the scientific impact of past, present and future observations by monitoring instruments

2 http://www.oato.inaf.it/blazars/webt/

or monitoring programs has been exemplified, as well as multi-wavelength and multi-messenger observations. Different techniques and instruments for TeV monitoring have been briefly presented pointing out the complementary of their achievements. TeV monitoring instruments play and will play an important role in our understanding of the TeV transient and variable sky.

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Abbreviations

The following abbreviations are used in this manuscript:

AGN	Active Galactic Nuclei
CTA	Cherenkov Telescope Array
EBL	Extra-galactic background
EC	External inverse Compton
FACT	The First G-APD Cherenkov Telescope
FoV	Field of View
FRB	Fast Radio Burst
GRB	Gamma-ray Burst
GW	Gravitational Wave
HAWC	High Altitude Water Cherenkov Gamma-ray Observatory
HBL	High-Frequency Peaked BL
H.E.S.S.	High Energy Stereoscopic System
IACT	Imaging atmospheric Cherenkov Telescopes
LAT-Fermi	Large Area Telescope instrument on board the Fermi satellite
MAGIC	Major Atmospheric Gamma-ray Imaging Cherenkov Telescope
M@TE	Monitoring at TeV Energies
MWL	Multi-wavelength
PWN	Pulsar Wind Nebulae
SSC	Synchrotron Self-Compton
ToO	Time of Opportunity
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VHE	Very High Energies

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