PROCEEDINGS OF SCIENCE

Synergies between CTA and VLBI

M. Orienti* **for the CTA Consortium**
INAF-IRA Bologna
E-mail: orienti@ira.inaf.it

Gamma rays are produced by the most powerful and often explosive physical processes in the Universe. Understanding the origin and role of relativistic cosmic particles in galactic and extra-galactic objects is among the key issue that will be addressed by the Cherenkov Telescope Array (CTA). With its huge improvement in sensitivity, angular resolution, energy range, and flexibility of operation, CTA will provide a step forward in our understanding of the gamma-ray emission in transients and active galactic nuclei (AGN). At the other extreme of the spectrum, radio Very Long Baseline Interferometry (VLBI), with its milliarcsecond imaging and polarimetric capabilities have long been the key tool in studying the relativistic outflows that are the likely sites of gamma-ray production in AGN. Furthermore, VLBI ultra-precise astrometry will be fundamental for the study of transient phenomena. In this contribution I will present an overview on the characteristics of CTA and on the science at high energy. Then, I will focus on the synergies between CTA and VLBI.

14th European VLBI Network Symposium & Users Meeting (EVN 2018)
8-11 October 2018
Granada, Spain

*Speaker.

PoS(EVN2018)047

1. Introduction

The gamma-ray sky provides a look into the most energetic and violent processes in the universe. High-energy emission has been detected from our Galaxy as well as beyond. Relativistic jets produced by Active Galactic Nuclei (AGN), supernova remnants, gamma-ray bursts are only some of the phenomena producing gamma rays and are target of gamma-ray observations by telescopes on board satellites, like *Fermi* and AGILE, and on ground, like VERITAS, H.E.S.S. and MAGIC experiments.

The Large Area Telescope (LAT) on board *Fermi* has been surveying the sky since August 2008 and has produced several catalogs, either generic on the gamma-ray sky, like the first, second and third *Fermi*-LAT source catalogs (FGL) [2, 22, 4], or specific on some class of objects like AGN [7], gamma-ray bursts [6], supernova remnants [5], and flaring objects [3] among others. The last generic catalog, the 3FGL, is based on 4 years of *Fermi*-LAT observations and consists of 3033 gamma-ray sources, with the largest population ($\sim$36%) of extragalactic origin. About 33% of the whole sample is made of unassociated sources and multi-wavelength campaigns have been undertaken to unveil their nature.

The energy range covered by gamma-ray satellites is mainly between tens of MeV to hundreds GeV, with *Fermi*-LAT operating from 20 MeV to above 300 GeV (see e.g. [8]). The sensitivity of current gamma-ray satellites decreases as we consider TeV energies. However, this energy window is well covered by ground-based gamma-ray telescopes.

Contrary to gamma-ray satellites, ground-based gamma-ray telescopes do not detect gamma-ray photons directly. In fact, when gamma-ray photons interact with the atmosphere they produce showers of subatomic particles. These ultra-high-energy particles travel at a velocity that is faster than light in air and create a blue flash of “Cherenkov light”, which is then detected and imaged by imaging atmospheric Cherenkov telescopes (IACT).

The number of gamma-ray sources detected so far by Cherenkov telescopes is 218 and they are listed in the TeV catalog TeVCat[1] and are part of different galactic and extragalactic populations. If we compare the number of TeV sources with the 8-year preliminary list of sources detected by *Fermi*-LAT, which consists of more than 5500 objects[2], it turns out that in the TeV energy range we are detecting only the tip of the iceberg, preventing population studies at very high energy (VHE, E>100 GeV). Furthermore, the sample of TeV sources is strongly biased because the majority of the observations were triggered by an increase of the average flux in other electromagnetic bands and half of the detections were made when the sources were in a flaring state. It is therefore clear that gamma-ray ground-based astronomy has a huge potential of discovery.

The Cherenkov Telescope Array (CTA) is the next generation of gamma-ray ground-based observatory and in combination with multi-wavelength and multi-messenger studies, will address many of the open questions concerning the high-energy phenomena in the universe.

Among the synergies that CTA will have with other wavelengths, the one with the radio band will be of particular importance, because gamma rays and radio wavelengths provide two windows on the non-thermal universe. Furthermore, radio very long baseline interferometry (VLBI) observations can achieve (sub-)milliarcsecond resolution, enabling a deep look into the compact regions

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

[2] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/

where particles are accelerated to the highest energy.

This contribution is organized as follows: a brief description of CTA and the science with CTA are presented in Sections 2 and 3, while synergies between CTA and radio VLBI are discussed in Section 4, and conclusions are reported in Section 5.

2. The Cherenkov Telescope Array

The Cherenkov Telescope Array is the next generation of imaging atmospheric Cherenkov telescopes and will be the first open proposal-driven ground-based gamma-ray observatory. It will observe the entire gamma-ray sky between 20 GeV and 300 TeV, widening the energy coverage of current IACT experiments and increasing the number of phenomena that can be studied. High sensitivity at low energies is mandatory for the study of the whole universe and in particular for objects at high redshift avoiding the gamma-gamma absorption on the extragalactic background light (EBL). On the other hand, the highest energies are fundamental for investigating the most extreme particle accelerators mainly from our Galaxy.
The large energy range required by CTA will be covered by three different types of telescopes[3]:

- the large-sized telescopes (LST), with a 23-meter diameter, will cover an energy range between 20 and 150 GeV. Their field of view is 4.3 degrees. In case of alerts LST should repoint in 30 seconds;
- the medium-sized telescopes (MST), with a 12-meter diameter, will cover an energy range between 150 GeV and 5 TeV. Their field of view is about 7.5 degrees;
- the small-sized telescopes (SST), with a 4-meter diameter, will cover an energy range between 5 and 300 TeV. Their field of view is about 9 degrees.

In addition to the wide energy coverage, CTA will improve the sensitivity at 1 TeV of an order of magnitude with respect to current IACT, reaching a flux sensitivity of about 10^{-13} erg cm^{-2} s^{-1} in 50-hr observation and enabling, for the first time, population studies at TeV energies[4]. As a comparison, 50-hr observations with VERITAS and H.E.S.S. reach a sensitivity at 1 TeV of about 6×10^{-13} erg cm^{-2} s^{-1}. The improvement in sensitivity is also significant on short (intra-day) timescales. For example, at 30 GeV the CTA sensitivity on minute time-scales will be better than 10^{-9} erg cm^{-2} s^{-1}, i.e. more than four orders of magnitude than *Fermi*-LAT. The sensitivity improvement on short time-scales in addition to the large field of view and the ability to promptly respond to alerts issued by other multi-wavelength and multi-messenger observatories will make CTA a unique instrument for the study of transient phenomena at very high energy, enabling, for the first time, the detection of classes of transients still undetected at gamma rays.
The sensitivity improvement is obtained by the large number of telescopes that will be located in

[3]More information on CTA telescopes and technology can be found at: https://www.cta-observatory.org/about/how-cta-works/

[4]https://www.cta-observatory.org/science/cta-performance/

PoS(EVN2018)047

the two hemispheres to allow the observation of the entire sky and to improve the chance to detect gamma-ray cascades [17]. The northern site will be in La Palma (Spain) and will consist of 4 LST and 15 MST (for an energy coverage between 20 GeV and 20 TeV) spread over 1 km^2. The southern site will be in Chile and will consist of 4 LST, 25 MST, and 70 SST (i.e. spanning the entire CTA energy range, 20 GeV $-$ 300 TeV) spread over 4 km^2. The choice of implementing SST only in the southern site is driven by the fact that the inner regions of our Galaxy, where the highest energy photons are expected, are visible only in the Southern Hemisphere.
Another key characteristic of CTA is the improvement in angular resolution and field of view which will increase the ability of imaging extended sources as well as performing surveys. Although at energies below 100 GeV the angular resolution remains worse than that of *Fermi*-LAT, at energies around 1 TeV and above it is about 0.05 degrees or better. As a comparison the angular resolution of VERITAS and MAGIC above 1 TeV does not go below 0.06 degrees. This ability is important for resolving very-high-energy sources in crowded environments like the Galactic centre and the Galactic plane.

3. Science with CTA

The unique capabilities of CTA will be crucial for addressing ambitious questions on the physics of high-energy universe. The main scientific topics that will be addressed by CTA are:

- Understanding the origin and role of relativistic cosmic particles, and in particular determining how and where particles are accelerated, how they propagate in the surrounding medium and what role, direct or indirect, accelerated particles play on star formation and galaxy evolution.

- Probing extreme environments, such as determining the physical processes close to compact objects, like neutron stars and black holes; characterizing relativistic jets, winds and explosions produced by compact objects; investigating radiation fields and magnetic fields in cosmic voids and their evolution.

- Exploring frontiers in physics, such as unveiling the nature and distribution of dark matter; determining quantum gravitational effects on photon propagation; discovering the existence of axion-like particles.

To address these themes, CTA will perform key science projects (KSPs) which have guaranteed time during the early life of CTA. The KSPs have been selected on their excellent scientific case and the significant improvement with respect to the state-of-the-art. KSPs will produce legacy datasets.
In addition to a rich Dark Matter programme, the KSPs focus on galactic and extragalactic science: from the study of the Galactic center and Galactic plane, to star forming systems and the Large Magellanic Cloud (LMC) in the near universe, up to AGN and galaxy clusters at large distances. As part of KSPs, CTA will perform surveys of specific regions of the sky: the Galactic plane survey, the LMC survey, and the extragalactic survey. Detailed information on the Science with CTA

can be found in [9]. Here we provide a short description of the topics with mutual interest between CTA and VLBI.

3.1 Extragalactic science

AGN are the manifestation of the extraordinary amount of energy released by a super massive black hole hosted in the centre of a galaxy. About 10% of AGN, called radio-loud AGN, form a bipolar outflow of relativistic plasma and magnetic field which may extend well beyond the host galaxy. When the jets form a small angle to our line of sight the emission is amplified by Doppler boosting effects and a high level of variability is detected at all wavelengths. These sources are termed blazars and represent a high fraction of the gamma-ray sky. Relativistic jets emit non-thermal radiation across the entire electromagnetic spectrum and their spectral energy distribution (SED) is characterized by two humps: one at low-energy, from radio to infrared/optical/X-rays, produced by synchrotron radiation, and the other at high energy, from X-rays to very high energy, produced by inverse Compton (IC) scattering (e.g. [13]). Depending on the position of the synchrotron peak frequency, blazars are classified as low-synchrotron-peaked (LSP), intermediate-synchrotron-peaked (ISP), or high-synchrotron-peaked (HSP) objects. In particular, the class of HSP blazars, whose IC hump is above a few hundred GeV, makes about 65% of the extragalactic sources detected at VHE by IACT, while LSP blazars, whose IC-hump is in the MeV/GeV range, dominate the source counts in the *Fermi*-LAT extragalactic sky [7].
Blazars may be also divided by their optical properties: flat spectrum radio quasars (FSRQ) have bright continua and broad lines, while BL Lac objects have almost featureless optical spectra. This dichotomy may reflect a physical difference in the accretion regimes, being radiatively efficient in FSRQ and radiatively inefficient in BL Lacs (see e.g. [15]).
In radio galaxies the jet forms a large angle to our line of sight and the emission is not significantly amplified, making these sources difficult to detect at high energy. Only 4 radio galaxies are present in the TeVCat to date, leaving many aspects on the physics of these objects poorly constrained.
A boost to our understanding of the physics of relativistic jets is among the main goals of the following KSPs.

Extragalactic survey KSP. This KSP consists of a blind survey of 1/4 of the sky with a uniform sensitivity of about 6 mCrab above 125 GeV. The proposed region has Galactic latitude $b > 5^{\circ}$ and Galactic longitude $-90^{\circ} < l < 90^{\circ}$. About 1000 observing hours spread over not more than three years, will be devoted to achieve the goal and both CTA arrays will be used. No extragalactic surveys have been performed by current IACT facilities so far, and no population studies have been conducted at very high energy. The predicted sensitivity will allow source population studies of the local universe, up to $z < 0.2$, and the determination of the luminosity function of gamma-ray AGN. Although sources at $z > 0.2$ will be below the survey sensitivity threshold during their low-activity states, they will be caught during an increase of their activity or during flares. Furthermore, serendipitous detection of fast transients is also foreseen (see Section 3.2).
This KSP will allow the discovery of new populations of gamma-ray emitting sources, like starbursts galaxies, Seyferts and low luminosity AGN. The detection of an increased number of VHE-emitting radio galaxies will improve our knowledge of their emitting mechanisms in the gamma

rays and determine their contribution to the isotropic gamma-ray background.

Active Galactic Nuclei KSP. Despite decades of efforts, many aspects of the physics at work in relativistic jets are still under debate. Thanks to the episodes of enhanced activity that characterize blazars, it is possible to constrain the physical properties of the jets, like the site of the high-energy emitting region, the mechanisms and the seed photons involved in the scattering process, by studying the variability timescales and comparing the observed variability in various energy band. The AGN KSP is divided into three main programmes:

- Long-term monitoring of a few prominent VHE emitting AGN up to at least ten years. The goal is to provide long term light curves and time-resolved spectra of outstanding objects from different classes of VHE AGN, from radio galaxies to (ultra-)HSP blazars in order to investigate their variability.
- High-quality spectra programme. The goal is to obtain high-quality spectra for about 40 AGN with different redshift and AGN class for a precise measurement of the EBL and for the study of the evolution of blazars with redshift. In addition, deep observations of the two nearest VHE-emitting galaxies, M87 and Centaurus A, will be performed to extract high-quality spectra and to search for extended emission.
- AGN flare programme. The goal is to perform follow-up observations of AGN detected during a flare (from external and self-triggered alerts, for example from the long term monitoring programme and the real time analysis). In addition, snapshots of a list of about 80 AGN from different classes (from radio galaxies to soft-spectrum FSRQ/LSP blazars and hard-spectrum (ultra-)HSP blazars) will be performed using CTA sub-arrays with a sensitivity of about 20% of the Crab nebula flux.

To maximise the scientific outcome from these KSPs, a combination with multi-wavelength and multi-messenger observations is crucial. For example, the comparison of the light curves and the determination of possible time lags in the observed variability at different energy bands may provide important information on the location and size of the gamma-ray emitting region and on the mechanisms involved. Furthermore, multi-wavelength observations of unassociated VHE sources that will be discovered by CTA will be fundamental for determining their low-energy counterpart and determine the nature of the objects.

3.2 Science of transients

One of the most violent and energetic phenomena in the Universe is represented by transients. Transients are a heterogeneous population of galactic and extragalactic objects that explode or flare up in dramatic and unpredictable fashion with a broad range of timescales and across the electromagnetic spectrum. Transients are associated with catastrophic events involving relativistic compact objects such as neutron stars and black holes. These events may take place in our Galaxy (like flares from pulsar wind nebulae and from magnetars, or jet ejection events from micro-quasars and other X-ray binaries, or explosions on the surfaces of white dwarfs), or may be extragalactic

PoS(EVN2018)047

(like gamma-ray bursts (GRBs), fast radio bursts (FRBs), high-energy neutrinos and gravitational wave (GW) transients).

Transients KSP. The unprecedented sensitivity on short timescales makes CTA the ideal instrument to study transient phenomena. This KSP aims to follow-up different classes of transients: GRBs, galactic transients, X-rays/optical/radio transients, GW and high-energy neutrino transients, serendipitous VHE transients. As already mentioned, several objects in our Galaxy are known to produce jets and outflows. However, their physical mechanisms are poorly understood and the detection by CTA may shed new light on these phenomena. Furthermore, despite expected, no VHE counterparts have been detected so far for some of these phenomena, like FRBs, and the detection by CTA of VHE emission may be used to test the proposed models. Furthermore, the large field of view of CTA offers the possibility to serendipitously discover transients from new and unexpected classes of objects.

4. Synergies between CTA and VLBI

Radio and high-energy observations provide two complementary views of the non-thermal universe. CTA observations will trace cosmic particle accelerators in galactic and extragalactic environments, and will study the physical processes at work in cosmic sources. Despite the improvement, the angular resolution at VHE is still not adequate for localising the acceleration zones. A crucial help comes from radio observations. The resolution on (sub-)milliarcsecond scales provided by VLBI observations allows a deep look into the innermost region of relativistic jets and outflows, enabling the localization of the acceleration zones. The location of the gamma-ray flaring region is still highly debated. Different scenarios locate this region in the innermost region of the AGN, within the BLR (e.g. [25]), while other scenarios suggest a location much further out, at pc-scale distance from the AGN along the jet (e.g. [20]). Furthermore, multi-epoch VLBI observations will allow follow-up of shocks propagating along relativistic jets/outflows. The possibility to perform full-polarization observations enables the study of the magnetic field structure in the cosmic accelerators.
Here we discuss how the synergy between CTA and VLBI can improve our knowledge of the high-energy processes.

Extragalactic science. The long term monitoring programme within the AGN KSP aims at building long-term light curves at VHE of a selection of blazars in order to determine their variability scales and investigate the physical mechanisms involved. The addition of VLBI observations is crucial for determining the region(s) where gamma-ray emission is produced. For example, in the case of NGC 1275 the *Fermi*-LAT and VLBI monitoring suggested that the central radio core is responsible for the short-term gamma-ray emission, while the long-term gamma-ray emission is likely produced by the new jet structure [18].
Concerning the AGN flare programme, VLBI observations may allow the localization of the high-energy emitting region by observing where the radio flux density increase is observed. In the case of TeV flare from M87, VLBI observations could detect radio variability about 120 pc downstream

PoS(EVN2018)047

along the jet, indicating that high-energy emission may be produced in sites other than the central AGN [10].
Multi-epoch VLBI observations allow us to discriminate the physical scenario, either one-zone or two-zone models, able to explain the broad-band SED of flaring objects that are part of the high-quality spectra programme of the AGN KSP. The detection of a superluminal jet component suggests that the multi-band variability is likely produced by a shock propagating along the jet, indicating that one-zone models are adequate to describe the flaring episode. The emergence of superluminal components seems to take place close in time with gamma-ray flares (e.g. [19]), while the radio outburst follows the gamma-ray flare with some time delay that increases with decreasing the observing frequency, in agreement with the formation of a shock and its evolution (e.g. [23]). On the other hand, in some TeV radio galaxies and BL Lacs (e.g. [16]), VLBI observations could resolve the transverse jet structure which shows a clear limb-brightened morphology that should be the observing manifestation of a velocity structure that may indicate that radio and gamma rays are produced in two different regions of the jet [26].
VLBI observations will be important also for the characterization of unassociated VHE sources that will be detected during the extragalactic survey. The association of VHE sources with the low-energy counterpart is usually a hard task owing to the large error ellipse at high energy. In fact, there may be several radio sources falling within the error circle, precluding the source association. However, gamma-ray emission should come from compact regions at the jet base, and not from extended lobe-dominated regions. VLBI is blind to scales larger than a few arcseconds, filtering away extended sources and detecting only blazar objects whose number is limited with only one usually falling within the error circle (e.g. [24]).

Science of transients. The high angular resolution of VLBI observations is crucial for the study of transient phenomena and the physics at their origin. Among Galactic transients, VLBI observations have provided important steps forward in our understanding of emission models and jet formation in accreting objects like microquasars [12], as well as of shocks in novae. Classical novae are the most common astrophysical thermonuclear explosions taking place on accreting white dwarf stars. The detection of novae at gamma rays indicates the presence of particle acceleration by strong shocks in the ejecta. VLBI observations of the gamma-ray emitting nova V959 Mon pointed out that the ejecta are shaped by the motion of the binary system with some gas expelled along the poles, while dense gas is drifted out along the equatorial plane. Synchrotron emission is observed at the interface between equatorial and polar regions, pinpointing the region where particle acceleration and gamma-ray emission are produced [11].
Among extragalactic transients GRBs are luminous and distant explosions still not well understood. GRBs are likely to originate from relativistic jets produced by either core collapse, or merger events of relativistic compact objects. Despite many efforts, the jet formation, particle acceleration, the emission site and its environment are highly debated. In this context, CTA may address the key aspects like the particle acceleration and the detection of the prompt phase at VHE, whereas VLBI observations can provide information on the medium in which the shock is propagating, like in the case of GRB 151027A, where VLBI measurements provided a direct evidence that the blast-wave is expanding not in a homogeneous medium, but in a medium shaped by the wind of the stellar progenitor [21].

PoS(EVN2018)047

As already mentioned, (short) GRBs may be produced by a binary neutron star merger, which is also a potential source of gravitational waves, like in the case of the GW event GW 170817 that was detected by the gamma-ray burst monitor on board the *Fermi* satellite as a short GRB 1.7 seconds after the GW detection by LIGO. This was the first, and the only one to date, GW with electromagnetic counterpart from radio to gamma rays [1]. Thanks to its large field of view, CTA follow-up of GW may offer better localization prospects if compared with other energy bands, through more efficient searches over wide areas of the sky for their electromagnetic counterpart. Furthermore, VLBI follow-up observations of the radio structure proved to be fundamental for determining which kind of jet was formed as a consequence of the merger: either a narrow relativistic jet that successfully breaks out of the ejecta, or a nearly isotropic mildly relativistic outflow which expands owing to its own pressure [14].
A particular emphasis should also be given to serendipitous VHE transient discoveries offered by the large field of view and the instantaneous high sensitivity of CTA.

5. Conclusions

The Cherenkov Telescope Array will be the ground-based gamma-ray observatory in the near future. CTA will be for the first time a ground-based gamma-ray open proposal-driven observatory, but in the first years a large fraction of time will be devoted to key science projects with very significant scientific promise and requiring considerable observatory time. Given its huge improvement in sensitivity, angular resolution and field of view, CTA is an explorer of the extreme universe and has broad scientific potential: from particle acceleration to dark matter and fundamental physics. CTA will have important synergies with many present and future multiwavelength and multimessenger observatories, like the Square Kilometer Array. The combined strength among different facilities will be crucial for new discoveries. In particular, high-energy and radio observations open two windows on particle acceleration and their synergy will provide a step forward in our understanding of the non-thermal universe.

6. Acknowledgment

We gratefully acknowledge financial support from the agencies and organizations listed here: http://www.cta-observatory.org/consortium_acknowledgments. This presentation/publication has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730562 [RadioNet]. The activities presented here are partly supported through a PRIN-INAF SKA-CTA grant.

References

[1] Abbott, B.P., et al., *Multi-messenger observations of a binary neutron star merger*, 2017, ApJL, 848, 12

[2] Abdo, A.A., et al., *Fermi Large Area Telescope First Source Catalog*, 2010a, ApJS, 188, 405

[3] Abdollahi, S., et al., *The Second Catalog of Flaring Gamma-Ray Sources from the Fermi All-sky Variability Analysis*, 2017, ApJ, 846, 34

[4] Acero, F., et al., *Fermi Large Area Telescope Third Source Catalog*, 2015, ApJS, 218, 23

[5] Acero, F., et al., *The First Fermi LAT Supernova Remnant Catalog*, 2016, ApJS, 224, 8

[6] Ackermann, M., et al. *The First Fermi-LAT Gamma-Ray Burst Catalog*, 2013, ApJS, 209, 11

[7] Ackermann, M., et al., *The Third Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope*, ApJ, 810, 14

[8] Atwood, W.B., et al., *The Large Area Telescope on the Fermi Gamma-Ray Space Telescope Mission*, 2009, ApJ, 697, 1071

[9] The CTA Consortium, *Science with the Cherenkov Telescope Array*, 2019, World Scientific, ISBN 978-981-3270-08-4, DOI 10.1142/10986 (arxiv 1709.07997)

Cherenkov Telescope Array, The: Acharya, B.S., et al., *Science with the Cherenkov Telescope Array*, 2017, arXiv:1709.07997

[10] Cheung, C.C., Harris, D.E., Stawarz, Ł., *Superluminal radio features in the M87 jet and site of flaring TeV gamma-ray emission*, 2007, ApJL, 663, 65

[11] Chomiuk, L., et al., *Binary orbits as the driver of gamma-ray emission and mass ejection in classical novae*, 2014, Nature, 514, 339

[12] Egron, E., et al., *Single-dish VLBI observations of Cygnus X-3 during the 2016 giant flare episode*, 2017, MNRAS, 471, 2703

[13] Fossati, G., Maraschi, L., Celotti, A., Comastri, A., Ghisellini, G., *A unifying view of the spectral energy distributions of blazars*, 1998, MNRAS, 299, 433

[14] Ghirlanda, G., et al., *Re-solving the jet/cocoon riddle of the first gravitational wave with an electromagnetic counterpart*, 2018, arXiv:1808.00469

[15] Ghisellini, G., Tavecchio, F., Foschini, L., Ghirlanda, G., *The transition between BL Lac objects and flat spectrum radio quasars*, 2011, MNRAS, 414, 2674

[16] Giovannini, G., et al., *A wide and collimated radio jet in 3C84 on the scale of a few hundred gravitational radii*, 2018, Nature Astronomy, 2, 472

[17] Hassan T., et al., *monte Carlo performance studies for the site selection of the Cherenkov Telescope Array*, 2017, Astroparticle Physics, 93, 76

[18] Hodgson, J.A., et al., *KVN observations reveal multiple gamma-ray emission regions in 3C84?*, 2018, MNRAS, 475, 368

[19] Jorstad, S.G., et al., *Multiepoch very long baseline array observations of EGRET-detected quasars and BL Lacertae objects*, 2001, ApJS, 134, 181

[20] Marscher, A.P., et al., *The inner jet of an active galactic nucleus as revealed by a radio-to-gamma-ray outburst*, 2008, Nature, 452, 966

[21] Nappo, A., et al., *The 999th Swift gamma-ray burst: some like it thermal*, 2017, A&A, 598, 23

[22] Nolan, P.L., et al., *Fermi Large Area Telescope Second Source Catalog*, 2012, ApJS, 199, 31

[23] Orienti, M., et al., *Radio and gamma-ray follow-up of the exceptionally high-activity state PKS 1510-089 in 2011*, 2013, MNRAS, 428, 2418

[24] Schinzel, F.K., et al., *New associations of gamma-ray sources from the Fermi second source catalogue*, 2015, ApJS, 217, 4

[25] Sikora, M., Begelman, M.C., Rees, M., *Comptonization of diffuse ambient radiation by relativistic jets: the source of gamma rays from blazars?*, 1994, ApJ, 421, 153

[26] Tavecchio, F., Ghisellini, G. *On the spine-layer scenario for the very-high-energy emission of NGC 1275*, 2014, MNRAS, 443, 1224