Prospectives IN2P3 - GT04 astroparticules

Extragalactic γ-ray Astrophysics

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The list of co-authors features prominent members of the community interested in and contributing to this branch of γ-ray astronomy, from both the IN2P3 and INSU institutes of CNRS. Numerous colleagues from CEA, unable to sign these contributions, are also leading researchers in this field. With this document, we affirm the strong support of the French community for the development of extragalactic γ-ray astrophysics, and for the fostering of links across the different relevant communities.

Abstract

The extragalactic sky at γ-ray energies is rich in sources. In the high-energy band, accessible to space-based instruments such as *Fermi*-LAT (MeV - GeV energy range), there are 3411 extragalactic sources of γ rays associated with known multi-wavelength (MWL) counterparts. At higher energies (GeV - TeV), accessible to ground-based Cherenkov instruments such as H.E.S.S., MAGIC and VERITAS, there are 83 extragalactic sources of γ rays. Across the γ-ray spectrum, the dominant source class is blazars, a subclass of active galactic nuclei (AGNs) with jetted emission pointed towards Earth, but there is also a notable emerging population of γ-ray bursts (GRBs) and of radio galaxies (AGNs with off-axis jets). Although very different classes of emitters, AGNs and GRBs have some important features in common, in particular, relativistic jets where particles are accelerated to extreme energies. The launching and collimation of these jets remains an open question in astrophysics, as does the nature of the particles accelerated there-in and the processes powering this acceleration. In addition to striving to understand the astrophysical processes at play in these sources, their study can help us to address long-standing open questions in physics, such as “where are the ultra high-energy cosmic rays accelerated?” and “how are supermassive black holes formed?”. They are a unique tool to study the physics of extreme environments, including accretion physics, jet formation and general relativity. Significant progress in the study of extragalactic γ-ray sources has been made with the current generation of γ-ray instruments. The dawn of the Cherenkov Telescope Array (CTA) era is upon us, so the next ten years will see exploration of the extragalactic γ-ray sky with unprecedented sensitivity. The first ever very high-energy survey of a large swathe of the extragalactic sky will give us the first unbiased view of the cosmos at these energies, allowing us to perform population studies and to perhaps discover new source classes. Frequent “snapshot” observations of a large sample of target AGNs will boost the probability of detecting flaring states and enable the construction of long-term light curves to better understand these extremely variable sources. Deep, frequent observations of representatives from each AGN source class, possibly exploiting the power of CTA sub-arrays, will enable the reconstruction of detailed time-dependant spectra, which will be tested against our state-of-the-art theoretical emission models. Access to multi-messenger (MM) alerts from gravitational-wave and neutrino observatories will enable rapid follow-up observations of these violent events, advancing the newly born field of MM astrophysics and increasing the number of GRBs detected in the GeV - TeV regime. The study of extragalactic sources of γ rays also allows us to investigate the nature of the intergalactic medium including the effects of Lorentz invariance violation, the composition of the cosmological diffuse photon and magnetic fields, and to search for exotic particles such as axions. These areas of study are discussed in a separate contribution (“γ-ray cosmology”). CTA will also observe a number of Galaxy Clusters and could, therefore, for the first time establish these massive structures as sources of TeV γ rays (CTA Consortium 2019, Chap. 13; “Cosmology with galaxy clusters” document in preparation for these prospectives). A separate document is in preparation for these prospectives giving a global overview of the science of CTA. We submit this contribution to highlight the extragalactic science (with a focus on AGNs and GRBs) that can be achieved with CTA and collaborating multi-wavelength and MM facilities. We state our strong support for this science.

Overview

Our knowledge of the extragalactic sky at γ-ray energies has been revolutionized by the *Fermi*-LAT, operating between ~100 MeV and 300 GeV, the so-called high-energy (HE) regime, and from the current generation of imaging atmospheric Cherenkov telescopes (IACTs), operating above ~100 GeV, the so-called very-high-energy (VHE) regime. In each of these energy regimes, AGN are the dominant γ-ray emitters corresponding to more than 60% of the HE sources (The *Fermi*-LAT Collaboration 2019) and to 35% of the VHE sources, with 78 out of the 225 VHE sources being AGN (TeVCat: http://tevcat.in2p3.fr; Wakely & Horan 2008). This latter number should, however, be considered as a lower limit as no extragalactic survey has ever been undertaken in the VHE regime; these 78 sources are the result of pointed, targeted observations towards specific AGN, often at times during which they were known to be in an elevated emission state from MWL triggers.

A second, important class of extragalactic γ-ray emitter is GRBs. *Fermi*-LAT has detected emission above 100 MeV from 169 GRBs, three of which have a detected signal above 50 GeV (Ajello et al. 2019). In the VHE regime, after many years of searching, the first GRB was recently detected: GRB180720B and, since then, VHE emission has been detected from two more GRBs (see TeVCat and references therein). They are thus an emerging class of VHE emitters that constitute compelling environments in which the acceleration and cooling timescales in relativistic particle flows can be studied. With gravitational-wave (GW) alerts now being responded to, GRBs represent an exciting class of objects to observe so as to advance our MM studies of the cosmos (see IN2P3 prospectives contribution “Multi-messenger astroparticle physics”).

French scientists are heavily involved in many aspects of extragalactic science with the current generation of instruments, including AGN observations with *Fermi*-LAT and with H.E.S.S. and GRB observations with *Fermi*. We are actively participating in the preparations for extragalactic science with CTA and are interacting with MM and MWL partners to ensure that we collaborate in an effective way so as to extract the maximum scientific return from all of our observations. We note here that various trans-institutional (INSU / IN2P3 / CEA) initiatives are under development within the French astrophysical community, which are strongly pluridisciplinary and MM in nature, involving not only the “traditional” wavelengths to be probed by optical telescopes including LSST, VLT, radio telescopes including LOFAR, MeerKAT, Nançay, NIKA2, SKA and MWL observatories such as SVOM, but also GWs and neutrinos. We state here our strong support and the need for these kinds of developments, especially for CTA. We also note the regrettable absence of an instrument sensitive at MeV energies, which could benefit the study of AGN and GRBs enormously (see Section 2.5).

1. ExGal2030: Perspectives for the coming decade

Fermi-LAT, in which French scientists are heavily implicated, has been approved by the NASA Senior Review Committee for operation until 2022 and has been invited to submit a proposal for the next Senior Review (2022) implying that operations could be extended to 2024. With the onset of CTA scientific operations expected in 2022 (“Phase 1 early science”), joint HE-VHE observations can be undertaken during the first half of the upcoming decade.

A Core Programme of observations has been defined for CTA, consisting of a number of major legacy projects, in which the French CTA community is deeply involved. This Core Programme is comprised of Key Science Projects (KSPs), which will be carried out by the CTA Consortium (CTA Consortium 2019). During the first 10 years of operation, 40% of the CTA observing time will be dedicated to the KSPs, four of which have a major or exclusively extragalactic component: the AGN KSP, the Extragalactic Survey KSP, the Transients KSP and the Galaxy Cluster KSP (see “Cosmology with galaxy clusters” document in preparation for these prospectives for a discussion of this last KSP). The majority of the remaining time will be allocated to guest observers from contributing countries, through the guest-investigator program. We invite the French MWL and MM communities to prepare for this guest-observer program and we look forward to partnering with French scientists outside of CTA to submit joint observing proposals so as to maximize the scientific output of CTA.

1.1 Active galactic nuclei

AGN are galaxies that harbour a supermassive black hole ($10^{6\text{-}9}$ $M_\odot$) at their centre. Certain subclasses of them eject relativistic outflows in the form of jets and thus offer us a laboratory in which to study the physics of the most extreme persistent accelerators in the universe. The majority of γ-ray AGN are blazars, a subclass of AGN whose relativistic emission is beamed towards us. They radiate across the entire electromagnetic spectrum and emit about half, or more, of their power in the γ-ray energy regime. They have been observed to be highly variable on all timescales investigated (multi-year-scale down to minute-scale) and thus are a prime target for MWL observations, so that their time-variable flux can be cross-correlated across energy bands. The source of AGN variability is not yet understood, in particular, what causes the variability time scale to be so short during intense flaring periods (Aharonian et al. 2007). Theoretical investigations feature the study of dissipation in the black-hole magnetosphere (Begelman et al. 2008, Levinson & Cerutti 2018, Parfrey et al. 2019.), internal shocks (Joshi & Böttcher 2011), and relativistic magnetic reconnection (Sironi, L. & Spitkovsky 2014), including state-of-the-art contributions by French scientists (Cerutti et al. 2012).

The broadband emission of blazars is characterised by two broad spectral bumps, the first peaking in the optical to X-ray regime and the second in the MeV to VHE γ-ray regime. The exact location of these peaks depends on the subclass of blazar and, sometimes, on the emission state in which it is observed. A major component of blazar research is concerned with understanding the differences between blazar subclasses, whether they form a so-called blazar sequence (Ghisellini et al. 1998) how a blazar can change its subclassification when it flares (Biteau et al. 2019; Valverde et al. 2019), and on which physical characteristics (accretion flow, black-hole mass and spin, evolutionary status) this subclassification depends (Foschini 2017). Additionally, it is desirable to broaden the range of blazar classes observed, notably to detect more of the extreme blazars, those objects whose second peak is found in the VHE regime and whose emission is characterised by a very hard intrinsic VHE spectrum.

Another hotly debated topic in blazar research is the nature of the radiating particles that power the emission observed in the second spectral peak. The first peak is broadly agreed to result from the synchrotron emission of relativistic electrons spiraling in the magnetic field of the jet. Many competing models have been invoked to explain the second emission peak. Often divided into leptonic and hadronic models, recent years have seen, however, the maturing of lepto-hadronic models, with prominent French contributions (Cerruti et al. 2015, Cerruti et al. 2019, Katarzynski et al. 2001 & 2003, Hervet et al. 2015). Would blazars be shown to have a significant hadronic component in their emissions, they would be a prime candidate for the accelerators of ultra high-energy cosmic rays. Neutrino observatories can play a key role here. Already, a tantalising indication for a joint detection of a high-energy γ-ray flare and high-energy neutrinos from the TeV blazar TXS 0506+056 has been presented (Ansoldi et al. 2019). This result has been discussed enormously in the scientific literature highlighting the importance of such observations[1]. A key step in moving forward with these modeling endeavours will be the acquisition of high-quality, γ-ray spectra and light curves simultaneous with those measured at lower energies and for different emission states of the source in addition to continued neutrino observations, with IceCube and the upcoming KM3Net. In this way, we can exploit both the spectral and temporal information to reconstruct time-dependent broadband spectra of the sources and search for coincident γ-ray/neutrino emission, which would be used to put our current emission models to a serious test.

A small number of radio galaxies, often referred to as “mis-aligned blazars”, have been detected at TeV energies, including Centaurus A and M 87 and, recently, extended γ-ray emission has been detected that coincides with the inner jet of Centaurus A (Sanchez 2018). This is the first detection of extension for an extragalactic TeV source. With CTA’s higher angular resolution and better sensitivity, the search for, and mapping of, extended TeV emission from other nearby radio galaxies will be a major goal. Recently, the Event Horizon Telescope (EHT) collaboration (including

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[1] Many of these references can be found here: http://tevcat.uchicago.edu/?mode=1&showsrc=309

scientists at IRAM) revealed the first image ever taken of a black hole (EHT Collaboration 2019); that at the centre of M 87. The exact location of the highly variable TeV emission from this radio galaxy is still a topic of debate. Magnetic field dragging by a rotating black hole can create a gap where particle acceleration, synchrotron (radio), inverse Compton (γ ray) emission and pair production compete with each other and generate variability. Future observations of M 87 with CTA in conjunction with the black hole images taken by EHT could help disentangle the various emission regions.

1.1.1 The AGN KSP

The AGN KSP is designed to play a key role in addressing the issues outlined above by employing various observational strategies on carefully selected target AGN, including many of which French scientists have studied individually with *Fermi*-LAT and current IACTs (e.g. Aharonian et al. 2009, H.E.S.S. Collaboration 2012, Chevalier et al. 2019). Data from this KSP will enable us to address one of the key CTA science themes, namely, probing extreme environments. Data taken through the exploitation of a reference sample of high-quality spectra and light curves from different subclasses of AGN will bring us closer to a comprehensive understanding of the different types of blazars, including the nature of their parent population, an endeavour that started in earnest with the cataloguing of the GeV sky with *Fermi*-LAT, in which scientists in France have played a key role (*Fermi*-LAT Collaboration 2019a & 2019b[2]). The extension of these population studies to higher energies, especially with the sensitivity afforded by IACTs, will deepen our understanding of each particular blazar subclass by allowing us to measure detailed spectra in quiescent and in flaring states and to explore extreme high-peaked BL Lac objects, a population only accessible in large numbers to instrument with high sensitivity in the GeV-TeV range. These kinds of studies are closely tied with those that will be enabled by the Extragalactic Survey KSP, which is discussed in Section 1.1.2.

French scientists have much experience in the modeling of blazar spectra (e.g. Boutelier, et al. 2008, Sanchez et al. 2015, Hervet et al. 2015, Cerruti et al. 2019), which will allow us to contribute significantly to the interpretation of CTA AGN data. In addition to detailed time-dependent spectral modeling, another key component of the AGN analysis will be temporal studies, for example the stochastic modelling of the long-term light curves up to frequencies unattainable with current instruments (Zech et al. 2019). Scientists in France have much experience in analysing the long-term, well-sampled light curves provided by *Fermi*-LAT (Britto et al. 2016, Valverde et al. 2017 & 2019) and in analysing the light curves including observational gaps from Cherenkov telescopes such as H.E.S.S. (H.E.S.S. Collaboration 2010). We will thus actively contribute to the study of AGN variability for CTA. The tools and analysis methods developed and the experience gained during the analysis of *Fermi*-LAT and H.E.S.S. data will be a valuable input to this research line. Variability at all wavelengths is one of the defining characteristics of AGN. Strong constraints on the size of the emitting region and on its bulk velocity due to light crossing-time arguments can be placed when rapid variability is detected. These observations challenge our understanding of acceleration and radiative scenarios in an unprecedented manner.

1.1.2 The Extragalactic Survey KSP

As mentioned above, almost all of the extragalactic sources of γ radiation in the VHE regime were detected during targeted observations. A small number (including 1ES 1312-423 in the field of view of CenA and HESS J1943+213 lying behind the Galactic plane) were detected serendipitously. Thus, our current view of the extragalactic sky at these energies is heavily biased. The CTA extragalactic survey KSP will allow us to construct an unbiased extragalactic source catalogue with a sensitivity to objects nearly 200 times fainter than the Crab Nebula. Secondly, it will allow us to construct a high-resolution map of the extragalactic sky between 50 GeV and 10 TeV. A third objective of the extragalactic survey is to search for unexpected and serendipitous VHE phenomena over a large portion of the sky; the survey will be optimised to detect flares by using a "snapshot"

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[2] We refer here to 4FGL and 4LAC but French scientists played a lead role in all of the *Fermi*-LAT catalogues published to date: 1FGL, 1LAC, 2FGL, 2LAC, 3FGL & 3LAC.

strategy in which multiple short observations are made on each sky position in order to detect flaring states whose intrinsic duration is longer than the observation. The potential for discovery with this KSP is large and possibilities include the discovery of extreme blazars, the serendipitous discovery of fast flaring sources, the discovery of γ-ray emission from as-yet undetected source classes[3] such as, for example, Seyfert galaxies or ultraluminous infrared galaxies.

1.2 γ-ray bursts

VHE emission was detected from GRBs for the first time in 2018. Thus, they are the newest class of TeV emitters and currently have three members in their ranks (GRB180720B, GRB190114C and GRB190829A). The most luminous cosmic explosions since the Big Bang, GRBs are also one of the most enigmatic classes of transients. Characterised by a “prompt” emission phase lasting from fractions of a second to thousands of seconds and an “afterglow” phase during which the emission decays gradually over hours to weeks or longer, these explosions have been divided into two categories: long GRBs (LGRBs), where the duration of the prompt emission is longer than 2 seconds and short GRBs (SGRBs) where it is shorter than 2 seconds (Piron 2016). It is postulated that both types of GRB emission originates from relativistic jets that have different progenitors for each subclass, stellar-core collapse events for LGRBs and merger events, such as the one that triggered GW170817 / GRB170817A for SGRBs. Many of the basic physical properties of new class of VHE GRBs remain poorly understood, such as the nature of the central engine and, similarly to AGN, the mechanisms and timescales of jet formation, particle acceleration and radiation (Inoue et al. 2019). GeV-TeV observations of GRBs can offer valuable insights into these issues. French scientists have played a key role in the analysis of data from the *Fermi*-GBM, the *Fermi*-LAT and from *Swift* (Ackermann et al. 2010, 2013, Salvaterra et al. 2012 Yassine et al. 2017) and continue this work within the SVOM Collaboration (Section 2.3).

1.2.1 The Transients KSP

One of the key strengths of IACTs is their large collection areas and, therefore, their high sensitivity to transient events. It follows then that CTA will have unprecedented sensitivity in VHE γ rays for transient phenomena and short-timescale variability (Funk et al. 2013). This could revolutionise our knowledge of cosmic transients. In addition to this deep sensitivity, the large field of view of CTA will enable it to serendipitously detect transients independently of alerts from other observatories. Six classes of targets are considered in the Transients KSP: GRBs, galactic transients such as flares from binaries, pulsar wind nebulae or magnetars, alerts from “transient factory” facilities at X-rays, optical and radio wavelengths, high-energy neutrino transients, GW transients and serendipitous VHE transients. A VHE transient survey will also be undertaken in conjunction with the Extragalactic survey KSP mentioned above.

2. Beyond the γ-ray spectrum

As discussed above, AGN and GRBs radiate across the entire electromagnetic spectrum. While the observations that we will undertake with CTA will address emission at the highest energies, they will benefit enormously from supporting and complementary observations at longer wavelengths and from MM astronomy.

2.1 Determination of the redshift of TeV blazars

Many TeV blazars lie at unknown redshifts making the interpretation of their γ-ray spectra difficult due to the unknown depth of extragalactic background light through which the γ rays travel. Without knowledge of this depth, the spectrum at the source cannot be determined. Crucial, therefore, to the

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[3] We note also that deep observations of selected galaxy clusters will be undertaken with CTA as part of the Galaxy Cluster KSP (CTA Consortium 2019 Chap 13), thus potentially adding another new, important source class to the TeV sky. Further discussion of this topic can be found in IN2P3 prospectives contribution “Cosmology with galaxy clusters”.

extragalactic science case of CTA is the measurement of the redshift of these TeV blazars. Efforts are already underway to determine these redshifts with the CTA Redshift Task Force (Pita et al. 2017) and we emphasise here the importance of this work and our support of it.

2.2 Multimessenger Observatories

A full discussion of the future of MM observations in France is provided in the “Multi-messenger astroparticle physics” IN2P3 prospectives document, on which many of us are co-signers. The era of MM astronomy has begun in earnest with the detection of GWs and γ rays caused by the coalescence of two neutron stars (GW/GRB 170817). Additionally, after many years of searching, VHE γ-ray emission has now been detected from three GRBs, confirming their tremendous acceleration power. The detection of joint GW / electromagnetic signals from a population of GRBs is now a major goal of future observatories. The tantalising association of high-energy neutrinos with the TeV blazar TXS 0506+056 demonstrates another emerging axis of MM astrophysics. The joint detection of high-energy neutrinos and γ rays from an AGN would be a strong indication of hadronic emission in AGN. We reiterate, therefore, our strong support of the MM efforts underway through the international collaborations in which French scientists participate.

2.3 The Space-based multi-band astronomical Variable Objects Monitor (SVOM)

We would like to also state the importance of the alerts and observations that will be provided by SVOM (Wei et al. 2016). As is demonstrated by *Swift*, a highly-versatile satellite with γ-ray, X-ray and optical capabilities is an important counterpart to AGN and GRB observations. In addition to providing GRB alerts and follow-up observations, such a satellite also supports MWL observations of AGN, crucial for their broadband spectral and temporal modeling. Like *Swift*, SVOM will be a highly-valuable satellite with its rapid slew capability, flexible operations, ground follow-up and instruments offering us MWL observations. We state here our strong support for the French participation in this mission. A full discussion of SVOM can be found in the prospectives document “The Science of SVOM at IN2P3”, on which many of us are co-signers.

2.4 Radio imaging of extragalactic jets

The recent announcement of an extended TeV emission in the nearby radio galaxy Centaurus A (Sanchez et al. 2018) sets new grounds to address the crucial question of the location of the γ-ray emitting region in AGN and of the possible reacceleration processes at play in jets (e.g. recollimation shocks, stratified jets, Hervet et al. 2017). With an angular resolution of a few arcminutes, CTA will be able to image nearby radio galaxies such as Centaurus A and M 87 on kpc scales and to locate the peak of the emission within dozens of parsecs. The French community is participating in many radio instruments (as discussed in the Overview Section). Synergies between CTA and radio observations of AGN and of GRBs will be crucial to the modeling of relativistic jets, especially in VLBI (cm and mm).

2.5 Participation in an MeV Instrument

The MeV range remains the uncharted territory of the electromagnetic spectrum. There is a crucial need for an instrument that would be capable of measuring polarisation and would, therefore, have a high angular resolution. The HARPO collaboration demonstrated for the first time the measurement of the polarisation of MeV γ rays (Bernard 2019). There is no MeV polarimeter currently approved in Europe, although detailed proposals were developed for e-ASTROGAM (De Angelis et al. 2017). Plans are afoot in the U.S. with AMEGO (McEnery et al. 2019). AGN and GRB science would benefit from an MeV polarimeter. GRBs emit the bulk of their radiation at MeV energies and detecting the polarisation signature of leptonic and hadronic models in blazars would place strong constraints on the radiating particles (Zhang & Böttcher 2013). An MeV instrument would also enable us to unveil the long-sought population of MeV blazars (Ghisellini 2019), thus giving us insights into their total number density at a given redshift. The discovery of a large number of such hosts of supermassive black holes at $z > 4$ could potentially put strong constraints on the study of their formation.

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