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Perspectives of blazar studies with future space missions

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Abstract Since the AGILE and Fermi launch, the synergy between gamma-ray experiments and other space and ground-based observatories has been the key to carry out multi-wavelength campaign aimed at understanding the physical mechanisms responsible for the the observed gamma-ray emission in astrophysical sources. Blazars are the best examples of astrophysical sources where this strategy has been applied. The big efforts put in place for blazars to obtain coordinated observations with a broad coverage of the electromagnetic spectrum are providing new diagnostics of the physical processes at work in these sources, raising a lot of challenges for the theoretical interpretation. These could be partially solved through further observations with ground- and space-based facilities, therefore requiring new advances in technology and mission profile design.

We will discuss how the lessons learned from current γ-ray observatories represent an important heritage for future missions expected to play a crucial role in the understanding of extreme phenomena in the high energy domain.

Keywords Gamma rays: observations · Blazars · Jetted sources · Instrumentation

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1 Introduction

Since the launch of AGILE and Fermi, a lot of efforts have been putting in place to understand if the common interpretation of the blazar emission processes was corroborated by the deep analysis of the big amount of multi-λ data available for this class of sources. The analysis of these simultaneous observations shows a variety of emission properties exhibited in active states ("flares"): some blazars show correlated variability in the two regions of the electromagnetic spectrum probing the sync and IC emissions, while others do not [1]. In the latter case, there are blazar flares with extremely high value of the Compton Dominance (CD, i.e., the ratio of the Compton peak to the Synchrotron peak luminosity), registered during remarkable high energy activities ([2–4]). In addition, the shape of gamma-ray spectra, extending well above energies where high gamma-ray opacity is expected, puts severe constraints on the site where gamma-rays are produced ([18]). Moreover, the timescale of variability at different energies is a further diagnostics to link the observed emission with the particle acceleration mechanism. Finally, the very recent results on the possible connection between gamma-ray and neutrino emissions in blazars have renewed the interest in hadronic processes, i.e. via proton-proton or proton-photon collisions with matter or radiation fields surrounding the central engine or within an ejected plasma flow (see [20] for a review).

The complex picture of the physical processes at work in these objects cannot be explained without a long-term monitoring at different energy bands providing the boundary conditions which lead the flaring activity. The monitoring is aimed at exploring any kind of variations in the central engine, accretion disk and then broad line regions and the topology of the magnetic field (through polarization measurements). This is a very expensive approach in terms of time and human resources, since they require noticeable efforts for on-ground telescope network (e.g., GASP-WEBT). It is the same also at high energies when pointed observations with space missions are needed. Having large field of view detectors both ground and space-based is the key to manage this type of observations. This is the advantage of AGILE and Fermi able to monitor a large fraction of the sky per day, providing both monitoring and triggers for gamma-ray sources. In the near future, this will be possible at different energy bands thanks to the next generation facilities devoted to the study of transient sources (SKA, LSST, CTA). The on-going and future neutrino and gravitational waves experiments will also benefit of this "cheap" monitoring of the transient sky, providing a larger set of candidate counterparts to be linked with the high energy emission.

It's worth noticing that the present issues and challenges require new measurements not possible with current facilities. New insights into the complex phenomenology of these sourcses could be achieved with future missions, planned or under study in the 2020s, with unprecedented timing, spectroscopic and polarimetric capabilities in the high energy domain. In the following sections, we will focus on possible advances achievable in the understanding of blazar physics with future X-ray and gamma-ray space missions.

2 Challenges and perspectives

In 2020s, the puzzling phenomenology of blazars will be complemented with X-ray polarimetric measurements provided by the incoming Imaging X-ray Polarimetry Explorer and possibly in gamma-rays with e-ASTROGAM (enhanced ASTROGAM). Moreover, The enhanced X-ray Timing and Polarimetry mission will combine polarimetric measurements with unprecedented timing capabilities, that will match those of future TeV observatories.

IXPE The Imaging X-ray Polarimetry Explorer (IXPE, [5]), selected in 2017 January as a NASA Astrophysics Small Explorer (SMEX) mission in collaboration with the with the Italian Space Agency (ASI), will enrich the information space for the study of cosmic sources with linear polarization measurements that will be added to the properties (time, energy, and position) observed in X-ray Astronomy (see Fig. 1). IXPE is planned for a launch in 2021 (low Earth orbit) and will measure the X-ray polarization of several point/extended sources in the 2-8 keV energy range, through the three telescopes aboard which host the innovative Gas Pixel Detectors able to perform imaging-capable polarimetry.

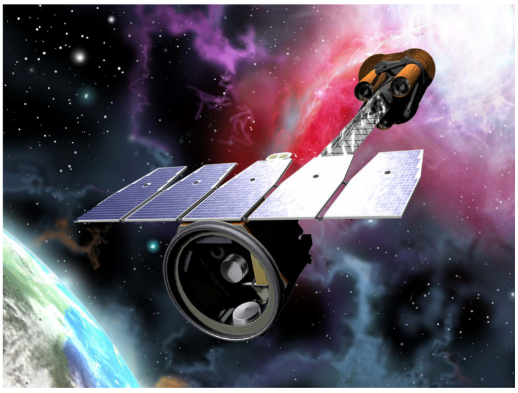

Fig. 1 Artistic concept of the IXPE missions described in the text (Credits: Nasa/Msfc).

eXTP The enhanced X-ray Timing and Polarimetry mission (eXTP, [**?**]) is a mission concept led by the Institute of High-Energy Physics of the Chinese Academy Sciences with a strong participation of European scientists planned for a launch in the mid 2020s. This mission is currently facing B Phase in China. The scientific payload is composed by 4 instruments covering the bandpass 0.5-30 keV: the Spectroscopic Focusing Array (SFA), the Polarimetry Focusing Array (PFA), the Large Area Detector (LAD) and the Wide Field Monitor (WFM) (see Fig. 2). The primary goal of this mission is to study conditions of extreme density, gravity and magnetism in and around compact objects in the universe, but a lot of additional science will be possible thanks to the combination of the 4 instruments aboard eXTP [6].

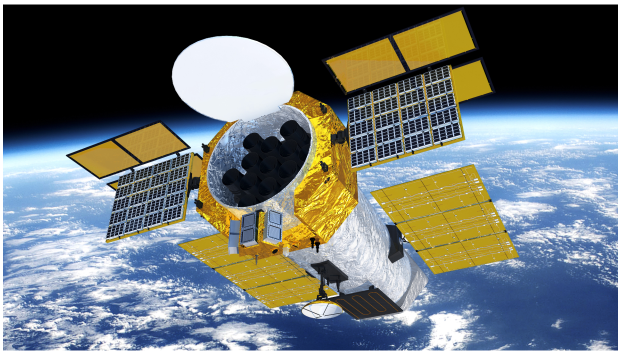

Fig. 2 Artistic concept of the eXTP missions described in the text (Credits: CAST).

eASTROGAM e-ASTROGAM (enhanced ASTROGAM, [7]) is a gamma-ray space mission, which will open a new window in the poorly explored MeV energy range. Composed by a Silicon tracker (without the tungsten converter of Fermi and AGILE), a calorimeter and an anti-coincidence system will be dedicated to the study of the non-thermal Universe in the energy range from 0.3 MeV to 3 GeV. This mission will probe a complementary energy range with respect to its predecessors (AGILE and Fermi) with unprecedented sensitivity, angular and energy resolution, combined with polarimetric capability. These capabilities in the MeV-GeV energy range will allow e-ASTROGAM to open a new window on the non-thermal Universe, providing pioneering observations for both Galactic and extragalactic sources (see Fig. 3).

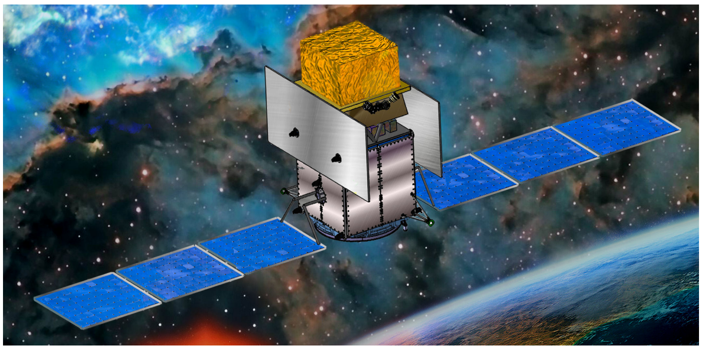

Fig. 3 Artistic concept of the eASTROGAM missions described in the text (Credits: INAF and INFN).

The availability of these data will help answering the most critical unsolved questions raised by current multi-wavelength campaigns devoted to blazar studies.

Among them: a) the origin of the photons undergoing Comptonization, b) the location of the acceleration region in jets (near to, or far from, the central black hole), c) the presence of additional components of accelerated electrons, with strong implications on the nature of acceleration processes such as shock or magnetic field reconnection, d) the hadronic origin of the high energy emission and neutrino connection.

2.1 Polarimetry and timing in the high energy regime

As reported in section 1, polarimetric measurements represent a crucial diagnostics for the investigation of particle acceleration mechanisms, hadronic vs. leptonic origin of the high energy emission, and nature of seed photons for Comptonization in blazars. This means that polarimetry significantly contributes to solve the most challenging questions raised by recent observations of blazars. In this respect, IXPE will provide the first polarimetric measurements of both High Synchrotron Peak BL Lac (HSP) and Low Synchrotron Peak blazars (LSP) in the energy range 2-8 keV, probing the region dominated by the sychrotron radiation and inverse Compton emission (in the common leptonic scenario), respectively. Among blazars, the HSP objects are the best candidates for IXPE, because they are bright in the energy range 2-8 keV (with even remarkable outbursts) and characterized by synchrotron radiation generally expected to be highly polarized (up to $\Pi \sim 70\%$ assuming a uniform magnetic field). Actually, the value of the polarization degrees observed in optical range between a few percents to $30-40\%$ [10], which might favor the multizone jet, where polarization is the average of multiple zones [11,9], each of them with a uniform magnetic field. In this respect, it is mandatory to perform simultaneous optical and X-ray polarization measurements, because the energy dependence of the polarization degree will put strong constraints on the electron particle acceleration process, magnetic reconnection vs. classical shock diffusive acceleration mechanism ([12]) and consequently the particle distributions. Assessing the role of reconnection or alternatively scenarios requires the additional capability of future instruments to detect ultra-fast variability of the high energy emission. In this respect, simultaneous polarimetric and timing measurements performed by eXTP, with the PFA and the LAD instruments, respectively, will clearly assess the nature of the electron population(s) responsible for the X-ray emission and therefore the particle acceleration mechanisms. Ultra-fast variability (minute timescale) has been detected only in the gamma-ray band, especially at TeV energies, at which the Cherenkov arrays are characterized by large collection areas, required to probe such short time cales (see the case of PKS 2155-304, [19]). This sets a clear synergy between eXTP/LAD and CTA observations, which will allow us to probe even shorter timescale of variability (seconds) in HBL objects. These very rapid variability phenomena unambiguously identify the occurrence of out-of-equilibrium particle acceleration likely produced by magnetic field reconnection with remarkably high efficiency.

For LSP sources, in the case of a leptonic origin of the high-energy emission, the high-energy radiation is a combination of synchrotron-self-Compton (SSC) and external-Compton (EC) emission, the latter caused by scattering of seed photons originating from outside the jet, such as the broad-line emission or the IR radiation of a dusty torus. The SSC radiation is expected to have 1/2 of the polarization degree of the synchrotron seed photon population that can be measured in the optical, with a polarization angle identical to the synchrotron radiation. On the other hand, in the EC emission case the polarization angle is related to the jet axis rather than to the magnetic field and the radiation is not polarized. This provides a powerful tool to make the first measurements of the relative relevance of SSC emission against EC in the X-ray spectra of leptonic jets in blazars. Alternatively, higher polarization degrees are expected in the case of hadronic process [13] or Bulk Comptonization of cold electrons in the jet [14,15]. Both IXPE and eXTP will be able to provide unique measurements in this respect, although this task can be accomplished for bright X-ray source ($\sim 2\times10^{-11}$ in 2-8 keV), or those with fainter flux but high optical polarization ($>$ 10%), on a reasonable timescale (a few $\times$100 ksec). In addition, position angle variations of the order of a few degrees can be provided on daily timescales. In addition to the LAD and PFA observations, the eXTP/SFA will provide with CTA observations a multi-wavelength perspective to understand better the rapid (unexpected) TeV emission detected in some FSRQs (e.g., 3C 279, 4C 21.35, PKS 1510-089) by involving temporal investigation on second time scales and spectral trend investigation on minute time scales.

The origin of photons and particle acceleration mechanisms can be effectively probed also with eASTROGAM both by much improved spectral measurements in the MeV-GeV band and by polarimetric observations in the MeV energy range. Polarimetry is indeed a powerful tool to establish the nature of the emitters (hadrons vs. leptons) and, in case of leptonic (i.e. inverse Compton) emission, the nature of the soft photon target radiation [13]. Given the sensitivity of eASTROGAM, the favored sources are LSP objects with the higher energy hump peaking in the MeV range.

In the 100 keV-10 MeV range, the polarization in leptonic emission models is low, while for hadronic models it is high and increasing in energy. Even in the presence of fields not well ordered, the polarization signature in the eASTROGAM energy band would be crucial in identifying a hadronic scenario for the brightest blazars [16]. Actually, the existence of gamma-rays produced by hadronic processes is very timely and still debated given the recent connection between neutrino and gamma-rays found in the case of IceCube-170922A, associated with the blazar TXS 0506+056 [17]. This possible connection triggered further investigations in both AGILE and Fermi observations coeval with neutrino detections (e.g., [21–23]). The recent findings show that this is a complicated task to be accomplished with current observations and polarimetric measurements in the MeV range would be crucial.

3 Conclusions

The huge amount of multi-λ data collected in the last decade under the boost of γ-ray experiments provided unprecedented information about the emitting power of this class of sources across the electromagnetic spectrum. In the meantime, these data drew a new picture of the emission mechanisms underlying the observational properties of blazars, which is indeed puzzling and therefore challenging for the theoretical modeling. The timescale of variability, the energetics during flaring activities (e.g., Compton Dominance), the emission properties (temporal and spectral variability) at low and high energy band, the Optical polarimetric measurements are difficult to be harmonized in a simple scenario, following the blazar standard models. Although different scenarios have been proposed in terms of particle acceleration mechanisms (magnetic reconnection) and topology of the magnetic field line (ordered vs helical magnetic field) many issues remain, leaving the floor to further investigations through next generation space and ground-based experiments. Moreover, the possible connection between gamma-rays and neutrinos, although still debated, is providing an additional boost towards theoretical modeling involving hadronic processes and their interplay with leptonic processes. In the future, new diagnostics will be provided by future experiments, able to survey the sky at different energies (SKA, LSST, CTA). This will offer the unique chance to have a long term monitoring of transient and variable sources, together with an improved capability to trigger follow-up observations in different energy ranges. Follow-up observations with current and incoming telescopes are mandatory to connect the long-term behavior of these sources with their flaring activity, poorly understood so far. In the next future, multi-λ polarimetric measurements will provide a new diagnostics in the investigation of magnetic field topology, multiple electron populations and nature of the seed photons of the IC emission. The NASA/SMEX mission IXPE is planned for launch in the spring 2021 forty years after the first measurement of the Crab Nebula with OSO-8. The pioneering observations provided by IXPE could be complemented by future observations with eXTP that will combine polarimetric and timing measurements of blazars, in a multi-frequency context (synergy with CTA and possibly eASTROGAM) characterized by enhanced capabilities to explore unprecedented timescales of variability. Future observations of blazars are therefore expected to solve most of the current issues, but at the same time they might lead to new challenges for theoretical interpretation.

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Conflict of interest

The authors declare that they have no conflict of interest.

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