The High Energy X-Ray Probe (HEX-P)

The most powerful jets through the lens of a superb X-ray eye

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Overview:

HEX-P is a probe-class mission concept that will combine high spatial resolution, X-ray imaging (<10 arcsec FWHM), and broad spectral coverage (0.1-150 keV) with an effective area far superior to current facilities (including XMM-Newton and NuSTAR) to enable revolutionary new insights into a variety of important astrophysical problems. The unprecedented observational capability of HEX-P will enable us to study the most extreme jets in the Universe powered by supermassive black holes. Its superior angular resolution will enable us to image the structure of these jets; its excellent sensitivity will unveil the bulk of their population in the early universe, close to the peak of their cosmic evolution; its timing capabilities will allow us to pin down acceleration and radiative processes responsible for the bulk of their X-ray emission; the simultaneous soft- to hard X-ray coverage will enable us to study in detail which particles are responsible for the high-energy emission. All in all, HEX-P is the ideal mission to unravel the science behind the most powerful jets in the universe, and the simulations presented here demonstrate so. More information on HEX-P, including the full team list, is available at https://hexp.org.

Introduction

The high-energy (E>10 keV) extragalactic sky is filled with active supermassive black holes. These monstrous objects, reaching masses of billions or more Suns, are feeding from the gas that surrounds them emitting copious amount of radiation. About 10% of such active galactic nuclei (AGN) also power relativistic jets from their core. When pointed close to the line of sight of the observer (at viewing angles <5-10°, [1]), these objects are named blazars.

Blazars are extremely bright multi-wavelength emitters (from radio up to TeV energies), reaching luminosities of ~10^{49} erg s^{-1}. Their broadband spectral energy distribution (SED) is characterized by two broad "humps", the low energy one peaking between IR-X-ray frequencies, and the high-energy one peaking in the X/γ-ray range. Blazars are extremely variable at all frequencies on timescales from day to months (e.g., [2]); their radio/optical and X-ray light is polarized; and they recently have been found to be neutrino emitters [3]. Although continuous multiband monitoring of these sources has been ongoing for more than 20 years, a lot of open questions remain on the nature of these extreme AGNs. For example, are the particles responsible for the high-energy spectral component leptons or hadrons (or a combination of both [4])? What processes energize the particles in the jet allowing them to produce such bright and rapid flares [5]? How many jets exist at the highest redshifts and what is their correlation to supermassive black hole growth [6]? Do they follow the so-called blazar sequence [7] or is it just a selection effect [8]?

HEX-P [9], with its simultaneous broad energy coverage at X-rays (0.1-150 keV), **will allow us to answer the above questions**. Synergy with current/future instruments such as COSI [10], IXPE [11], CTA [12] and the IceCube Gen2 [13] observatory will be **pivotal for blazar and multi-messenger science**.

Clues towards particle acceleration mechanisms

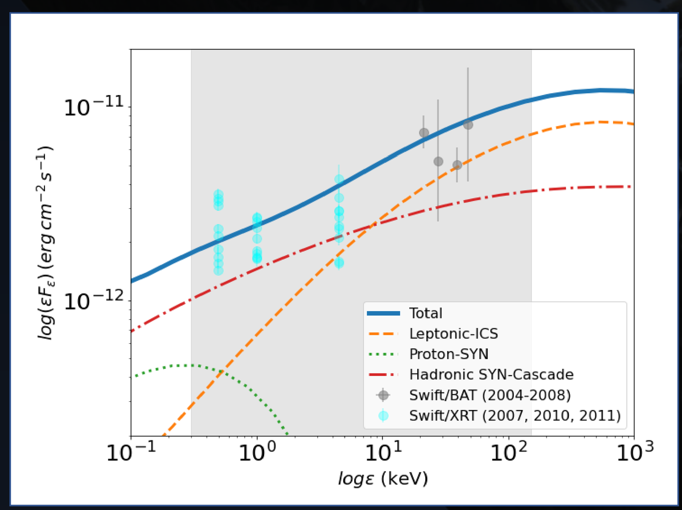

Figure 1. Theoretical X-ray spectrum of blazar Ap Librae (blue line), decomposed into its leptonic (orange curve) and hadronic (red and green curves) contributions. Markers show historical non-simultaneous observations. HEX-P, with its broad spectral coverage (grey region) and sensitivity will be ideal for the search of hadronic signatures in X-ray spectra.

The high-energy blazar spectral component may be produced by one or multiple radiation processes. Under the leptonic model, it is explained as inverse Compton radiation of the electrons in the jet; under the hadronic model, the hadronic cascading component can be considerable in the X-ray to MeV range [14]. In either case, **the hard X-rays mark the transition from one radiation process to the other** (Fig. 1). With its great spectral resolution and broad band coverage, HEX-P will be able to identify which one radiation mechanisms produces the high-energy component.

One of the main discoveries in the last decade has been the detection of flux variations close to or below the light-crossing time scale of the SMBH. Very rapid variability has been studied so far in a few exceptional flares, which have given rise to more sophisticated scenarios than the standard emission models (e.g., turbulent, multi-zone emission or magnetic reconnection, [6]). As shown in Figure 2, **for the first time HEX-P will be able to probe hours/day-timescales variability simultaneously at both soft and hard X-ray energies**, enabling us to disentangle a preferred particle acceleration process.

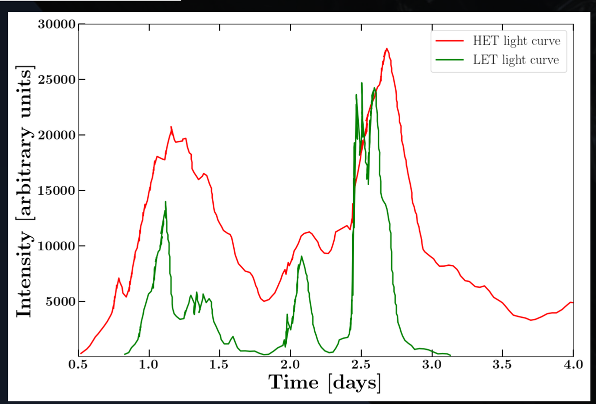

Figure 2. Light-curves produces by kinetic plasma simulations in the soft and hard X-ray regime of a blazar with a magnetic reconnection model (e.g. [6]). The simultaneous coverage of HEX-P will enable us to: probe such short timescale variability (~day time-scale) and disentangle if such variability is caused by different acceleration models.

Resolving Nearby Jets

Jets of active galaxies can be hundreds of kiloparsecs long, and their extended components have been observed in various energy bands. In particular, *Chandra* revolutionized the field by detecting kpc scale jets in soft X-rays (E<10 keV). The X-ray emission jet is usually interpreted as inverse-Compton radiation of electrons scattering the CMB, or as synchrotron emission of highly relativistic electrons. Moreover, the discovery of extended very-high-energy γ-ray emission in the radio galaxy Centaurus A requires likely scattering off dust emission or starlight [16].

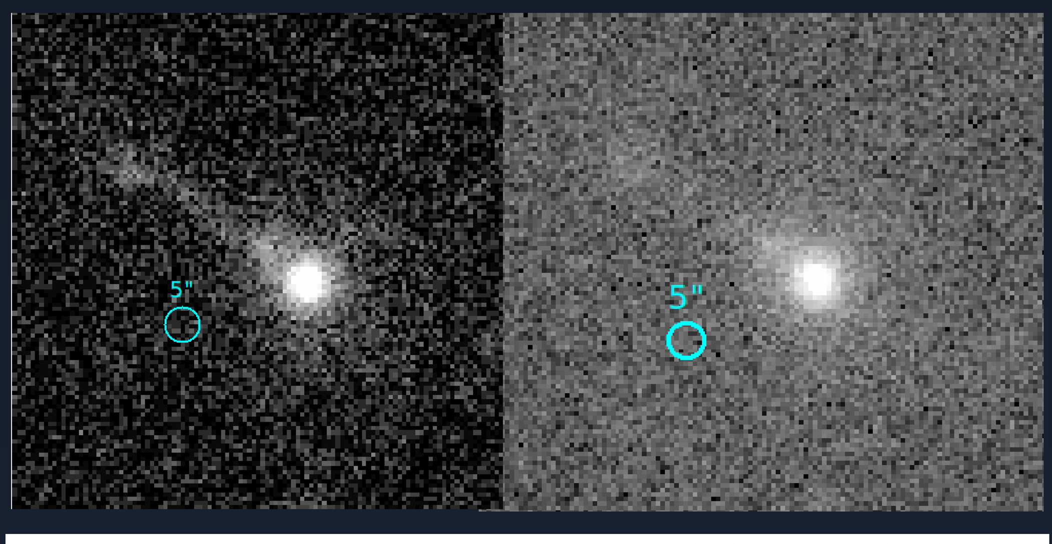

Figure 3. Simulated SIXTE image of Cen A as imaged by the LET (left) and the HET (right) onboard HEX-P.

Observations with HEX-P will be crucial in order to resolve for the first time the hard X-ray emission of nearby jets. The instruments angular resolution of 5" is sufficient to resolve nearby jets at hard X-rays in order to discriminate between the core and the jet emission. Figure 3 shows a preliminary simulation realized with SIXTE of **Centaurus A as seen for the first time by** the low and high energy telescopes (LET and HET) of **HEX-P**.

Multi-messenger connection

The blazar TXS 0506 has been the first blazar identified as a neutrino emitter in coincidence with its γ-ray flare [3]. Neutrinos are the key signature of hadronic processes. However, the non simultaneous **multi-messenger SED** (shown in Figure 4, [5]) of this source has yet to be understood in view of current blazar emission model. Crucially, simultaneous soft-hard X-ray coverage of such sources would be critical to disentangle particle radiation models and contributions. **Coordinated observation of HEX-P with future neutrino detectors (IceCube Gen2, [13]) would be key to disentangle jet particle composition**.

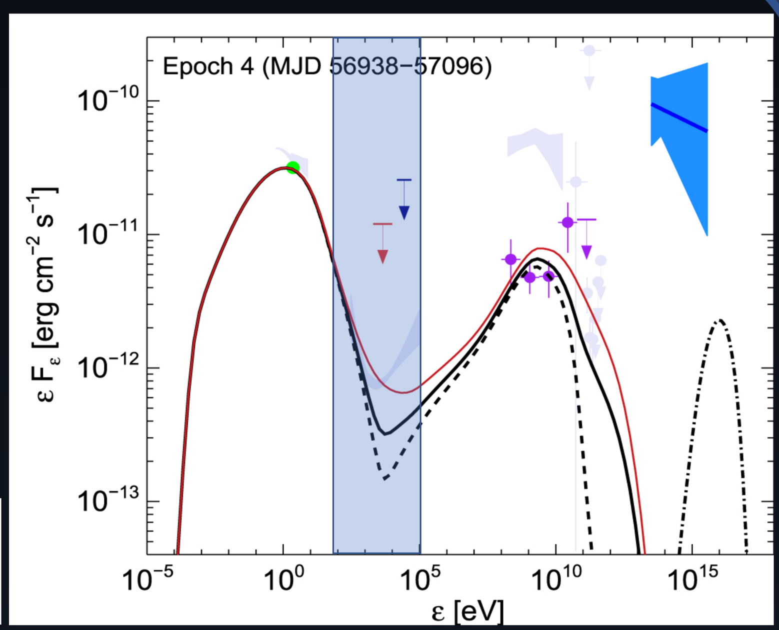

Figure 4. Broad band SED of TXS 0506 during the neutrino orphan flare in 2014/2015, from [5]. Lack of simultaneous broadband observations in the X-ray band severely hampers determining which model better describes the observed SED. The blue shaded region highlights the area that will be probed simultaneously by HEX-P, marking the transition from the low-energy to the high-energy components, a crucial energy window for disentangling particle emission properties.

Blazar classes

1. Broad line blazars - Flat Spectrum Radio Quasars (FSRQs, i.e. blazars with strong broad emission lines) are generally associated with strong jet emission, peaking at low frequencies both in synchrotron and inverse Compton components. Their high-energy component dominates the X-ray emission, particularly the rising section of the hump. The two instruments onboard HEX-P guarantee that **with a single observatory, the IC component of low peaked blazars and FSRQs can be mapped throughout cosmic time** (e.g. [16,17]) by focusing on the evolution of its shape, the amount of possible absorption in its softest section, and its possible variability.

2. Extreme BL Lacs - observations in the last two decades have unveiled a group of BL Lacs (i.e., blazars lacking optical emission lines) whose high-energy emission peaks at extreme energies, and thus called extreme BL Lacs [18]. Because of its unique combination of broad-band coverage and large collection area with imaging also in hard X-rays, HEX-P is ideally suited to study these objects, for 2 main reasons: 1) with SEDs peaking in the hard X-rays, HEX-P will be able constrain the peak location and particle spectrum much better and at much lower fluxes than any of the previous X-ray telescopes; 2) it perfectly matches the order of magnitude improvement above 1 TeV of the upcoming Cherenkov Telescope Array (CTA), enabling for the **first time the measure and study of the flux and spectral correlations of the hard X-ray with the hard TeV emission**. Simultaneous X-ray and TeV gamma–ray observations will be able to trace the evolution of the electron population responsible for the source bulk luminosity in these objects, providing a powerful diagnostic tool to probe the inner jet conditions, particle acceleration and evolution of the electron distribution.

3. Blazar sequence: observationally, there seem to exist an anti-correlation between the synchrotron peak position and the intrinsic luminosity of blazars, the so-called *blazar sequence* (Figure 5, [7]). Opponents of the sequence however argue that this is a mere selection effect [8]. A mission such as HEX-P will enable us to resolve this issue. On one hand, HEX-P extreme sensitivity will enable us to **detect hundreds of sources beyond z>4** as predicted by current X-ray blazar evolutionary models [6] (probing the low end of the blazar sequence). On the other hand, the sensitivity of HEX-P could enable us to **discover a handful of MeV peaked BL Lac sources in the local universe**. Predicted by the blazar sequence, these jets may have been missed by current surveys as too faint or overwhelmed by galaxy emission. If found, they will ensure the existence of such physical sequence.

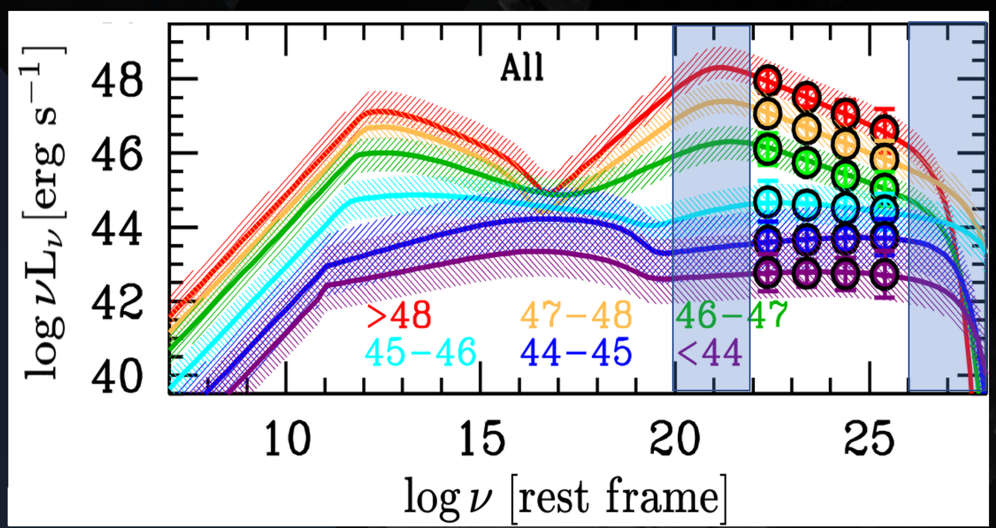

Figure 5. Blazar sequence as studied by [7]. The power of HEX-P will rely on detecting the faint ends of both the most-luminous (at high-redshifts) and the least luminous (in the local Universe) blazars (blue shaded regions), confirming (or not) the observational sequence.

Conclusions

A unique mission such as HEX-P, with its broad band X-ray coverage and unprecedented sensitivity and angular resolution at the hard X-rays, will enable us to answer several open science questions regarding blazars. HEX-P will allow us for the first time to (1) resolve jets at hard X-rays; (2) detect spectral signatures that will uniquely point us to the preferred high-energy emission mechanisms in jets, and by extension their composition; and (3) in synergy with the current and upcoming landscape of experiments (COSI, IXPE, CTA, IceCube Gen 2), reveal the preferred particle acceleration and multi-messenger emission mechanism of the brightest objects in the Universe, **fulfilling the promises of multi-wavelength and multi-messenger science**.

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Do you have ideas for how HEX-P would revolutionize your science? Get in touch!

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