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

Broadband studies of ultraluminous X-ray sources

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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. We will present simulations of HEX-P observations of ultraluminous X-ray sources (ULX) in nearby galaxies, showing how HEX-P will (1) study in detail populations of ULXs in a fraction of the time required by NuSTAR, pushing by a factor ~25 the high-energy sensitivity. (2) characterize their hard-energy spectrum, with much higher sensitivity than NuSTAR, looking for high-energy cyclotron resonance features; and (3) perform detailed timing studies of these sources thanks to the very low background and the enhanced response in the energy ranges where pulsations are stronger. More information on HEX-P, including the full team list, is available at https://hexp.org.

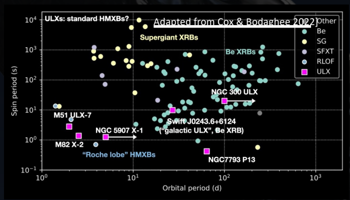
Ultraluminous X-ray sources (**ULXs, see** Kaaret+17 for a review) are extragalactic, off-nuclear X-ray sources whose apparent luminosity exceeds the Eddington limit for a stellar-mass black hole (10^{39}erg/s). The suggestion that these were intermediate mass black holes (**IMBH**) has over time lost traction due to the discovery of neutron star-powered ULXs (M82 X-2, Bachetti+14) reaching luminosities above 10^{41}erg/s (e.g. NGC5907 X-1, Israel+17), relegating IMBHs as plausible candidates only for the higher end of luminosities (e.g. HLX-1, Farrell+09), above 10^{42}erg/s.

ULXs are extragalactic objects. Some galaxies, such as M51 and NGC 253, contain a relatively large number of ULXs, and only Chandra, so far, was able to fully separate their emission. It is possible that a population of elusive, highly absorbed ULXs, have so far escaped detection (or identification as ULXs) from Chandra

A common feature of most ULXs are peanut-shaped curved spectra, with thermal components below 0.5 keV and additional thermal (or cutoff-powerlaw) components dominating above 5 keV and cutting off above ~10 keV. Hard X-ray coverage from NuSTAR was key to establish these cutoffs (Bachetti+13, Walton+13, Rana+15). When pulsations are present, they are usually associated with stronger hard components (e.g. Pintore+17, Walton+18).

The study of ULXs would strongly benefit from a high-angular resolution, hard X-ray mission with good timing capabilities.

Like HEX-P.



What we know

Many, if not all, ULXs are **powered by neutron stars**. Considering their complicated timing behavior, their distance and their position, the fact that we detected pulsations in six of them indicates that there are **many more still undetected**, plus possibly non-pulsating neutron stars.

ULXs are **super-Eddington** accretors. Besides their luminosity, this is also known from their huge optical and radio **bubbles** extending over up to 400 pc, their relativistic **winds** (e.g. Pinto+16, Walton+16).

From the few cases where the mass of the donor was constrained (from optical observations or pulsar timing), there is increasing evidence that ULXs are mostly **high-mass X-ray binaries**.

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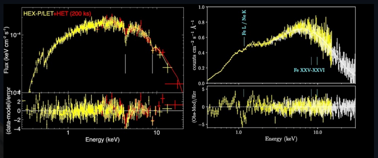
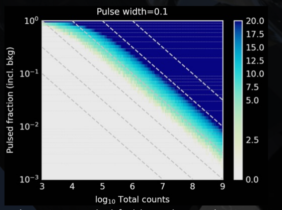


HEX-P will improve detectability of absorption/emission signatures from ULXs.
Left: Cyclotron Resonance Scattering Feature at 4.5 keV, and harmonic at 9 keV, from M51 ULX-8, as detected by a single 200-ks observation with HEX-P [credits: Brightman].
Right: Broadened wind signatures, undetectable in reasonable timescales with current gratings, detected at $> 3\sigma$ in 250 ks with HEX-P [credits: Pinto].

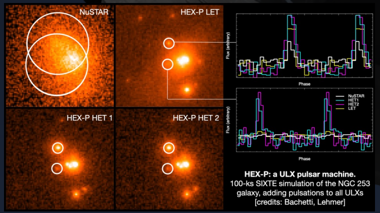
With its high sensitivity and angular resolution, HEX-P will study the spectra of many new ULXs. The improved effective area and background will allow not only to identify ULXs, but also to detect important spectral features such as emission and absorption lines associated with strong winds, or cyclotron resonance features (CRSFs) that allow a direct measurement of NS magnetic fields (See Figure). HEX-P can detect in ~50 ks the CRSF candidate of NGC 300 ULX (NuSTAR+XMM needed 180 ks, Walton+18, Koliopanos+19), and study it in great detail in 100 ks.



Pulsation sensitivity is mostly a matter of two instrumental characteristics: effective area and background level., but not in the same way. The sensitivity to pulsations increases linearly with signal strength and *quadratically* with source-to-background ratio. ULXs are in crowded field, and background is bound to be high.

Pulsars in crowded fields such as pulsating ULXs are the ideal playground for a mid/high-resolution imaging instrument like HEX-P. Where non-imaging timing-dedicated missions would suffer from extreme source confusion, HEX-P will see single sources with very minor overlap. The HET instrument of HEX-P can detect M82 X-2 in 4.5 ks, where NuSTAR needed 30 ks and RXTE was unable to detect it.

The intrinsically hard emission of pulsating ULXs and the commonly higher variability at harder energies add an additional dimension where HEX-P has an advantage over most other imaging observatories, typically only sensitive at softer X-ray energies.



HEX-P: a ULX pulsar machine.
100-ks SIXTE simulation of the NGC 253 galaxy, adding pulsations to all ULXs [credits: Bachetti, Lehmer]

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

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Open questions and where to address them

Low spin frequencies: an observational bias or a physical limit?
It is possible that a thick accretion curtain, or some reprocessing from the walls of the accretion-driven winds, quenches variability at high frequencies (e.g. Mushtukov+19). Discovering high-frequency pulsations would partially rule out these effects.

Orbital decay: mass transfer? Or something else?
M82 X-2 shows orbital decay consistent with the rate expected from super-Eddington mass transfer from an O/B star to a NS, compatible with the observed luminosity (see Bachetti+22), but also with other processes observed in HMXBs. Measuring this decay in other systems is key to understand the process, and maybe help finding…

… their progenitors? Their descendants?
Evolutionary simulations show relatively short lived and unstable phases of similar accretion from high-mass. Are ULXs young and doomed? Is there a way to sustain longer high mass transfer? Also, can ULXs can be fast tracks to form binary compact objects, and which ones? Finding more ULXs and their counterparts, and measuring their evolution, is key to answer this question.

How luminous are they, really? And why?
The luminosity of ULXs remains mysterious. Geometrical collimation from a disk wind is not enough to explain such an extreme luminosity. A high and non-dipolar NS magnetic field, is a possible explanation (Mushtukov+15, Israel+17, Brice+21).

HEX-P
HIGH ENERGY X-RAY PROBE

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