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The high energy X-ray probe (*HEX-P*): sensitive broadband X-ray observations of transient phenomena in the 2030s

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HEX-P is a probe-class mission concept that will combine high spatial resolution X-ray imaging (<10″ FWHM) and broad spectral coverage (0.2–80 keV) with an effective area superior to *NuSTAR* above 10 keV to enable revolutionary new insights into a variety of astrophysical problems, especially those related to compact objects, accretion and outflows. *HEX-P* will launch at a time when the sky is being routinely scanned for transient gravitational wave, electromagnetic and neutrino phenomena that will require the capabilities of a sensitive, broadband X-ray telescope for follow up studies. These include the merger of compact objects such as neutron stars and black holes, stellar explosions, and the birth of new compact objects. A response time to target of opportunity observation requests of <24 hours and a field of regard of 3π steradians will allow *HEX-P* to probe the accretion and ejecta from these transient phenomena through the study of relativistic outflows and reprocessed emission, provide unique capabilities for understanding jet physics, and potentially revealing the nature of the central engine.

KEYWORDS

transients: neutron star mergers, transients: black hole-neutron star mergers, transients: black hole mergers, transients: supernovae, transients: fast blue optical transients

1 Introduction

X-ray transients comprise some of the most interesting and energetic events in the Universe, and are usually powered by the birth of, accretion onto, and mergers of compact objects such as black holes and neutron stars. Surveys for astrophysical transients are now possible through electromagnetic, gravitational wave, and neutrino searches. As these transient surveys become more prevalent and more sensitive, it will be essential to have the capability to study the X-ray emission from the transients they uncover over a wide a range in energy and fluxes in order to understand the physics at their core.

Starting in the 2030s, the next-generation of gravitational-wave observatories are expected to come online, namely, the Einstein Telescope (Punturo et al., 2010; Maggiore et al., 2020), the Cosmic Explorer (Reitze et al., 2019), and the space-based *Laser Interferometer Space Antenna* (*LISA*; Amaro-Seoane et al., 2017). These observatories will detect the mergers of neutron stars and black holes out to large cosmological distances with improved sky localizations that will significantly increase the chances to identify their electromagnetic counterparts. The future of optical transients will be dominated by the Vera Rubin Observatory and its large synoptic survey where 1–2 million alerts are expected per night, as well as one million new supernovae from Rubin's Legacy Survey of Space and Time (LSST; Ivezić et al., 2019). A rich sample of transients at longer wavelengths will also be found by the next-generation radio observatories, particularly by the Square-Kilometer Array (SKA; Dewdney et al., 2009) and its pathfinders which are already in operation, such as the Australian SKA Pathfinder (ASKAP, Johnston et al., 2008) and the South African MeerKAT (Jonas et al., 2016). In the UV, *ULTRASAT* is approved for launch and will deliver a large number of UV transients (Shvartzvald et al., 2023). NASA is also currently concluding the down-select for the next Medium Explorer, both of which emphasize time-domain capabilities: either the *Ultraviolet Explorer* (*UVEX*) observing at UV energies providing large field of view UV photometry and rapid spectroscopy, or the *Survey and Time-domain Astrophysical Research eXplorer* (*STAR-X*) observing at soft X-ray and UV energies, is expected to launch at the end of this decade. Finally, the next-generation of neutrino detectors, namely, the KM3NeT in the Mediterranean Sea (Katz, 2006), the Gigaton Volume Detector in Lake Baikal (Baikal-GVD; Belolaptikov et al., 1997), and IceCube-Gen2 at the South Pole (Aartsen et al., 2014) also promise to yield a rich new view of the high-energy Universe, including stellar explosions.

Polzin et al. (2022) presents a compilation of all known classes of X-ray transients to date, covering a wide range in type, flux, and timescale (Figure 1). These range from low-luminosity events typically seen in our Galaxy, such as X-ray binary outbursts, to high-luminosity events seen in other galaxies, such as tidal disruption events (TDEs–e.g., Rees, 1988; Evans and Kochanek, 1989; Auchettl et al., 2017; Gezari, 2021). Both of these examples are produced by the accretion of stellar material onto a compact object such as a neutron star or a black hole. Polzin et al. (2022) also includes X-ray transients produced by the possible formation of a compact object, such as supernovae (SNe–e.g., Chevalier and Fransson, 2017) and more recently discovered fast blue optical transients (FBOTs–e.g., Drout et al., 2014; Arcavi et al., 2016; Ho et al., 2021), which might also be manifestations of (super-Eddington) accreting compact-objects.

The Probe-class *HEX-P* mission (Madsen et al., 2023) will provide sensitive broadband X-ray observations including roughly an order of magnitude improvement in the 10–30 keV band over *NuSTAR*, with significantly sharper angular resolution than either *XMM-Newton* (below 10 keV) or *NuSTAR* (above 10 keV). This sensitivity over a broad X-ray band will revolutionize the field of high-energy transient science, as shown in Figure 2 (adapted from Polzin et al., 2022), which shows that the faintest well-sampled lightcurves of each transient type to date will all be easily detected by *HEX-P* in the 10–30 keV band at early times.

Below we describe the *HEX-P* mission and the transient science for which we expect *HEX-P* to provide invaluable insights. We begin with the electromagnetic counterparts to gravitational wave events, followed by FBOTs, and SNe. We will also describe how *HEX-P* will yield insights into changing-look AGN (CLAGN), TDEs, blazars and fast radio bursts (FRBs) which are covered in more detail in separate papers (Kammoun et al., 2023; Marcotulli et al., 2023; Alford et al., 2023).

2 Mission design

The *High-Energy X-ray Probe* (*HEX-P*, Madsen et al., 2023) is a probe-class mission concept that offers sensitive broad-band X-ray coverage (0.2–80 keV) with exceptional spectral, timing and angular capabilities. It features two high-energy telescopes (HETs) that focus hard X-rays and one low-energy telescope (LET) that focuses lower-energy X-rays.

The LET consists of a segmented mirror assembly coated with Ir on monocrystalline silicon that achieves an angular resolution of $3.5''$, and a low-energy DEPFET detector, of the same type as the Wide Field Imager (WFI; Meidinger et al., 2020) onboard *Athena* (Nandra et al., 2013). It has 512×512 pixels that cover a field of view of $11.3' \times 11.3'$. The LET has an effective passband of 0.2–25 keV, and a full frame readout time of 2 ms, which can be operated in a 128 and 64 channel window mode for higher count-rates to mitigate pile-up and faster readout. Pile-up effects remain below an acceptable limit of $\sim 1\%$ for fluxes up to ~ 100 mCrab in the smallest window configuration. Excising the core of the PSF, a common practice in X-ray astronomy, will allow for observations of brighter sources, with a typical loss of up to $\sim 60\%$ of the total photon counts.

The HET consists of two co-aligned telescopes and detector modules. The optics are made of Ni-electroformed full shell mirror substrates, leveraging the heritage of *XMM-Newton* (Jansen et al., 2001), and coated with Pt/C and W/Si multilayers for an effective passband of 2–80 keV. The high-energy detectors are of the same type and flown on *NuSTAR* (Harrison et al., 2013), and they consist of 16 CZT sensors per focal plane, tiled 4×4, for a total of 128×128 pixel spanning a field of view slightly larger than for the LET, of $13.4' \times 13.4'$.

The response time to target of opportunity (ToO) observation requests will be <24 hours enabling fast observations of transient events. As shown in Figure 2 this will be more than enough to observe and detect and characterize all known X-ray transients in the 10–30 keV band while they are still bright. Furthermore,

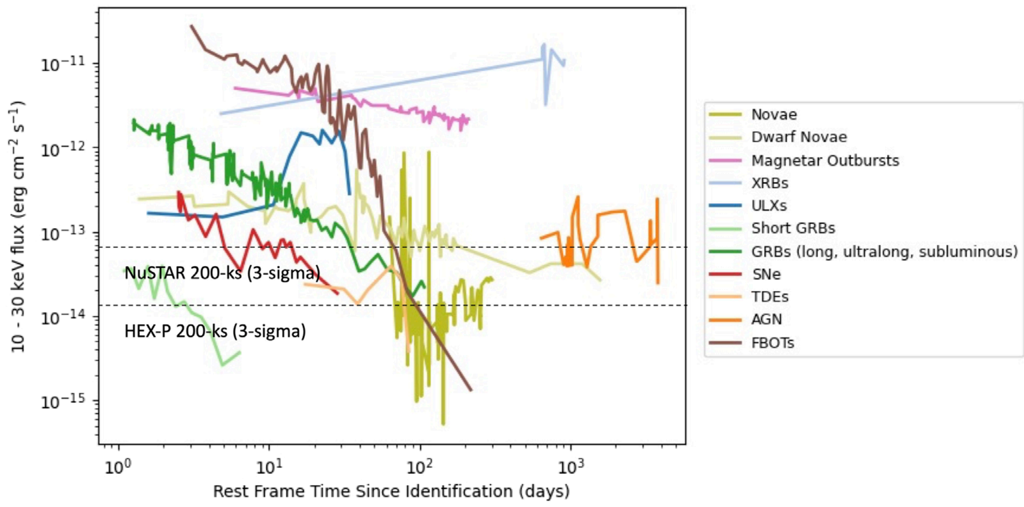

FIGURE 1
10–30 keV X-ray lightcurves of known X-ray transients, adapted from Polzin et al. (2022), with the sensitivities of *HEX-P* and *NuSTAR* shown with dashed lines. *HEX-P* will probe deeper in sensitivity than *NuSTAR* while matching *XMM-Newton* and *Chandra* at lower energies. This will enable sensitive broadband studies of all known X-ray transient types from ≤ 1 day post identification.

FIGURE 2
Artist impression of *HEX-P* showing the two high-energy telescopes (HETs) that focus hard X-rays and one low-energy telescope (LET) that focuses lower-energy X-rays. To achieve the high energies, HEX-P features a 20-m extendable boom, wrapped in a thermal sock to reduce motions.

HEX-P's location at L1 will allow a large fraction of the sky to be observed at any one time - the field of regard will be 3π steradians. This will also enable the fast observation of transient events.

The broad X-ray passband, superior sensitivity, fast response time and large field of regard will provide a unique opportunity to enable revolutionary new insights into the wealth of transient astrophysical phenomena that the facilities discussed above are expected to discover.

3 Simulations

All simulations presented in the following sections, specifically Section 4.3 and 4.4, were produced with a set of response files that represents the observatory performance based on current best estimates as of Spring 2023 (see Madsen et al., 2023). The effective area, ~340 cm^2 at both 1 keV and 30 keV when combining the LET and HET, is derived from raytracing calculations for the mirror design including obscuration by all known structures. The detector responses are based on simulations performed by the respective hardware groups, with an optical blocking filter for the LET and a Be window and thermal insulation for the HET. The LET background was derived from a GEANT4 simulation (Eraerds et al., 2021) of the WFI instrument, and the HET background was derived from a GEANT4 simulation of the *NuSTAR* instrument. Both assume *HEX-P* is in an L1 orbit.

4 New insights into transient phenomena by HEX-P

4.1 Probing the ejecta and remnant emission from the mergers of neutron stars and black holes detected in gravitational waves

With the detection of the first binary black hole merger in 2015 (Abbott et al., 2016), LIGO-Virgo opened a new gravitational wave window onto the Universe. This new era of multi-messenger astronomy with gravitational waves expanded with the LIGO-Virgo detection of GWs and photons from the binary neutron star merger GW170817 (Abbott et al., 2017), which yielded a wide range of scientific results, informing us about gravitational physics, nucleosynthesis, extreme states of nuclear matter, relativistic explosions and jets, and cosmology (e.g., Cowperthwaite et al.,

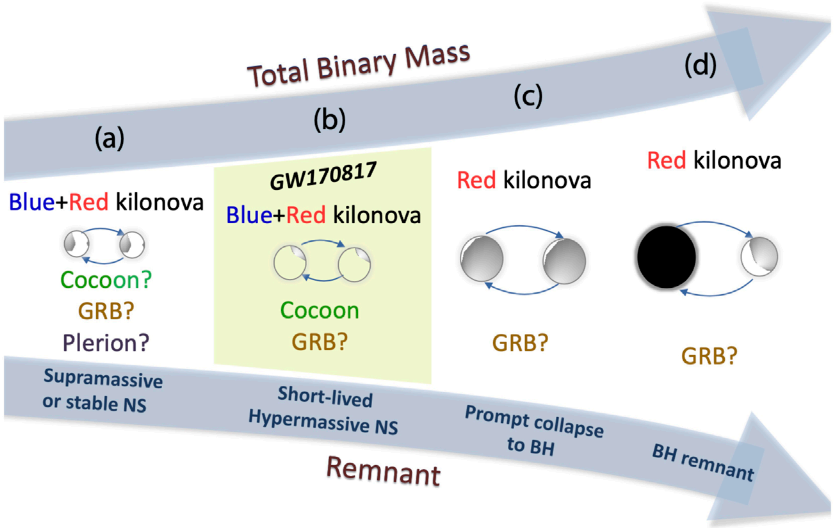

FIGURE 3
The range of binary neutron star and neutron star-black hole merger events expected to produce an X-ray afterglow being **(A)** a supramassive or stable NS, **(B)** a short-lived Hypermassive NS, **(C)** a prompt collapse to BH or **(D)** a BH remnant. *HEX-P* will provide a powerful tool for studying and understanding these extreme events.

2017; Margutti et al., 2017a; Troja et al., 2017; Margutti et al., 2018; Mooley et al., 2018b; a; Margutti and Chornock, 2021; Mooley et al., 2022).

The X-ray emission from GW170817 was produced by the collision between the fastest moving collimated ejecta and the circumburst medium (Margutti et al., 2017a; Troja et al., 2017; Margutti et al., 2018; D'Avanzo et al., 2018; Hajela et al., 2022). GW170817 represents only an initial exploration of a rich scientific landscape populated by stellar evolution, explosions, and eventual mergers of massive binary systems, and there are still many unknowns regarding the outcome of binary neutron star and neutron star-black hole mergers. The total binary mass and binary mass ratio, as well as the nature of the final remnant, governs the mass, velocity, and direction of ejecta outflows and should lead to a diverse range of electromagnetic counterparts. For example, the properties of the associated explosion, known as a kilonova, is expected to depend on how long lived a hypermassive neutron star (HMNS) may last before collapsing to form a black hole (Figure 3). If black hole formation is prompt, a red kilonova that peaks in the near-infrared is expected, otherwise, a longer-lived HMNS could produce a bluer kilonova (e.g., Metzger and Fernández, 2014). The neutron star equation of state is also expected to affect the kilonova properties (Zhao et al., 2023).

For binaries with significantly lower total mass than GW170817, does a long-lived supermassive or stable neutron star remnant form? *HEX-P* has the potential to observe emission from the merger remnant, be it a black hole or neutron star. Murase et al. (2018b) calculates the expected X-ray emission from the merger remnant, which, depending on the nature of the remnant, they predict would come from the disk of a newly formed black hole or the pulsar wind nebula (plerion) of a newly formed neutron star. In both cases, the emission would be highly absorbed at early times due to the remnant being buried in the merger ejecta (Figure 4). Hard X-rays would thus be the first to emerge, followed by softer X-rays as the ejecta become optically thin. Indeed, in the recent example of SN 2023ixf in the nearby Pinwheel Galaxy (M101; d = 6.9 Mpc), Grefenstette et al. (2023) report on *NuSTAR* observations a highly absorbed X-ray spectrum 4 days after the explosion and likely would have detected it sooner if the observation had taken place earlier. Soft X-ray observations by *Swift* did not detect the supernova until 4.25 days post-explosion (Panjkov et al., 2023). Naturally, an X-ray observatory with hard X-ray sensitivity such as *HEX-P* will be well suited to detect this kind of early and evolving remnant emission.

Assuming a distance of 40 Mpc, Murase et al. (2018b) predicts that the 30 keV emission from a black hole merger remnant would peak at $\sim10^{-14}$ erg cm^{-2} s^{-1} approximately $\sim10^{6}-10^{7}$ s post-merger (i.e., weeks to month timescales). *HEX-P* could reach these sensitivities at 30 keV (3σ) in a 500 ks observation. The emission from a neutron star is expected to be significantly brighter and therefore detectable to larger distances and/or shorter exposures.

X-ray lightcurves for events as bright as GW170817 provide a powerful means of probing ejecta properties such as energy and angular structure. From these bright events we can determine which binary neutron star mergers are capable of launching ultra-relativistic jets (e.g., Nathanail et al., 2021; Sun et al., 2022). Potentially, all binary neutron star mergers generate ultrarelativistic jets. If only some do, what determines the behavior? *HEX-P* will be able to detect the afterglow emission from a neutron star-neutron star merger at distances up to 200 Mpc under a range of jet scenarios, and characterize its lightcurve across multiple energy bands, thereby answering these questions. We illustrate this in Figure 5 which shows lightcurves calculated from hydrodynamic simulations of a binary neutron star merger based on the semi-analytic code used in Lazzati et al. (2018). The model has five free parameters: the viewing angle θ_v, the microphysical parameters ϵ_e (the fraction of shock energy given to electrons) and ϵ_B (the fraction of shock energy given to tangled magnetic field), the electrons population distribution index p, and the external medium density

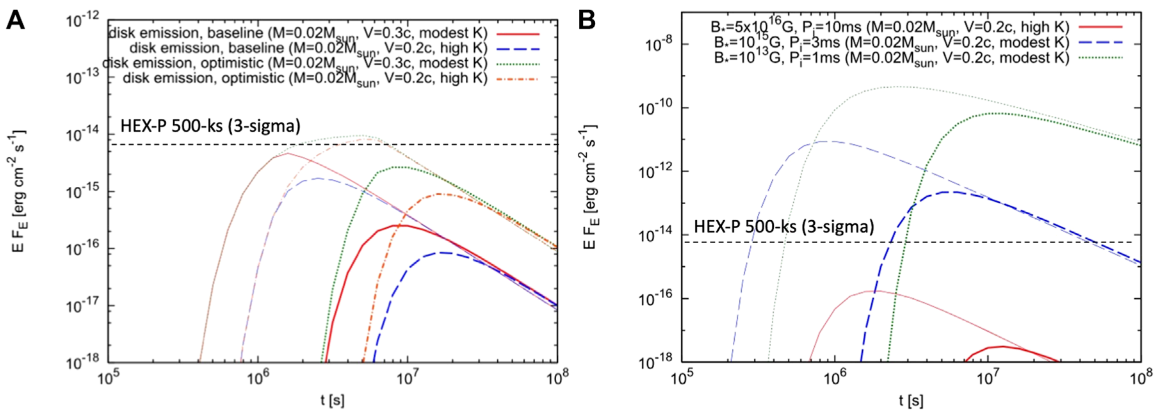

FIGURE 4
Predicted X-ray lightcurves of emission from an accretion disk of a black hole remnant **(A)** and emission from a pulsar wind nebula of a neutron star remnant **(B)** taken from Murase et al. (2018b) with *HEX-P* sensitivities at 30 keV shown. In both cases, emission at 30 keV (thin lines) emerges prior to and is stronger than emission at 3 keV (thick lines) due to the remnant being buried in the merger ejecta which is initially optically thick.

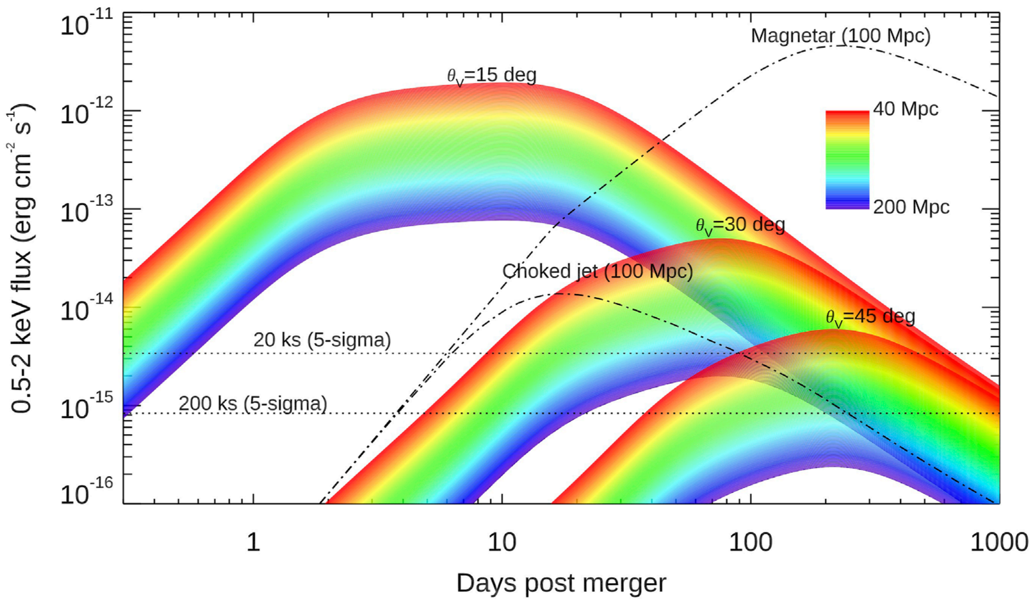

FIGURE 5
X-ray lightcurves calculated from hydrodynamic simulations of a binary neutron star merger at distances of 40–200 Mpc and circumburst density of 0.1 cm^{-3}. Our simulation includes outflow from the jet interacting with the interstellar medium, with viewing angles of θ_V = 15, 30 and 45°. We also plot a prediction for a choked jet and the magnetar model. *HEX-P* sensitivities are shown with dotted lines.

$n_{\rm ISM}$, which was assumed to be 0.1 cm^{-3} and constant. The total kinetic energy of the fireball and its initial Lorentz factor, both dependent on the viewing angle, were taken from a hydrodynamic numerical simulation previously described in Lazzati et al. (2017). Specifically, the energy of the blast wave, set by the numerical simulation, is 6×10^{49} erg. Our simulation includes outflow from the jet interacting with the interstellar medium, with viewing angles of θ_V = 15, 30 and 45°.

For a binary merger with significantly more mass than GW170817, we might expect a prompt collapse to a black hole. Although the formation of jets and cocoons is uncertain, the detection of the X-ray and radio afterglows may be able to disambiguate binary neutron star mergers from neutron star-black hole mergers of similar total mass. For neutron star-black hole mergers where the neutron star is disrupted beyond the innermost stable circular orbit, the tidal ejecta is expected to have much higher mass ($\sim 0.1 M_\odot$) than in a binary neutron star merger, and could yield a bright red kilonova. An absence of polar ejecta in this case would imply that jets, if launched, would escape to produce a short gamma-ray burst. However, there are large uncertainties and many unknowns in these predictions. *HEX-P*, with spectral and timing capabilities over a wide bandpass, as well as <24 hr response time and good sky visibility, will be well positioned to observe the range of X-ray emission from the ejecta of neutron star-neutron star and neutron star-black hole mergers.

4.2 Black hole-black hole mergers in AGN accretion disks

Binary black hole mergers come from two broad classes: a binary star evolutionary channel and a dynamical, or hierarchical, channel (for a recent review, see Mapelli, 2021). Among dynamical mergers, sub-channels include mergers in globular clusters, mergers in quiescent galactic nuclei, and mergers in the accretion disks of active galactic nuclei (AGN). Since the most massive stars end their lived in pair instability supernovae which leave no compact remnant, the explosive deaths of massive stars are not thought capable of producing black holes in the "upper mass gap" range above $\sim 50 M_{\odot}$. Massive binary black hole merger progenitors above $\sim 100 M_{\odot}$ therefore strongly imply a hierarchical merger origin, i.e., from consecutive merger events. This, in turn, implies a dynamical origin, not a field binary origin.

Since black holes can receive a strong kick at merger, mergers remnants are more easily retained in deep gravitational potentials, such as in the nuclei of galaxies. A promising location for hierarchical mergers are therefore AGN (McKernan et al., 2019). Merger kicks, even of large magnitude, are insufficient to escape an AGN environment, making AGN ideal for retaining and growing black holes via hierarchical mergers. AGN are expected to dominate the rate of mergers in the deep potential wells of galactic nuclei. Besides massive binary black hole mergers, other pointers to a significant contribution to binary black hole mergers from the AGN channel include highly asymmetric mass ratio black hole mergers and the observed anti-correlation between binary black hole mass ratio and effective spin (Callister et al., 2021), which at present can only be explained in the context of the AGN channel (McKernan et al., 2022).

Unlike all other merger channels, detectable counterparts are expected from compact object mergers in AGN due to the baryon-rich, high density environment. Simple scaling arguments imply that the luminosity of the counterpart should scale roughly linearly with the binary total mass (McKernan et al., 2019), implying more massive gravitational wave events create more luminous flares. Indeed, the first event with a candidate optical counterpart, reported by (Graham et al., 2020), was later identified as the most massive LIGO/Virgo merger observed to date, with a total mass of $150 M_{\odot}$ (Abbott et al., 2020). Kimura et al. (2021) present a model of how compact object mergers in AGN accretion disks should appear, with outflows creating a bubble in the AGN accretion disk, and the merger remnant black hole subsequently recoiling into the dense AGN disk and producing strong X-ray outflow-breakout emission that can outshine the AGN.

Though we are currently at very early stages, both theoretically and observationally, for understanding binary black hole mergers in AGN accretion disks, there are strong arguments to expect that this is an important gravitational wave merger channel, and that broadband X-ray emission will be a key tool for studying such events. We also note that counterparts to black hole mergers in accretion disks provide a test of the dynamics of the merger and a probe of fundamental AGN disk properties (Vajpeyi et al., 2022). In addition, associated counterparts (i.e., spectroscopic redshifts) to gravitational wave mergers enable their use as a standard siren, providing a new, independent measurement of the Hubble constant (Chen et al., 2022). *HEX-P* is well posed to become an important tool for studying both binary black hole mergers in AGN accretion disks, as well as the larger population of gravitational wave merger events over a range of environments.

4.3 Observing a potentially newly-formed compact object in fast blue optical transients

With the wealth of large area optical surveys such as the Zwicky Transient Facility (ZTF) and the upcoming Vera Rubin Observatory, a vast array of optical transients have been uncovered, with orders of magnitude more sources expected in the 2030s. Fast evolving luminous transients, or fast blue optical transients (FBOTs) are one such new class (Drout et al., 2014; Arcavi et al., 2016; Ho et al., 2021). Their fast evolution with rise times of <10 days and high luminosity in excess of 10^{43} erg s^{-1} imply a power source incompatible with the standard radioactive decay model for supernovae and can be explained by prolonged energy injection from a central compact object. Only a handful of such events have been discovered so far and are thought to comprise <0.1% of the local supernova population (Ho et al., 2023).

The best studied FBOT to date is AT 2018cow which, at a distance 60 Mpc, reached a peak X-ray luminosity of $\sim 4 \times 10^{44}$ erg s^{-1} (Margutti et al., 2019). One of the defining properties of this event was its luminous and variable X-ray emission unprecedented among optical transients. A *NuSTAR* observation ~7.7 days after discovery revealed an excess of hard X-ray emission above the soft X-ray power-law which is well modeled by reflection from Compton-thick material, i.e., the reprocessing of X-rays in an optically-thick medium such as an accretion disk. Reflection spectra are characterized by the presence of Fe K fluorescence emission lines near 6.4–6.9 keV, an absorption Fe K-edge at ~ 7–9 keV, and a broad featureless hump peaking at 20–30 keV produced by electron scattering. Modeling the high-energy spectrum of AT 2018cow required aspherical ejecta. The reflection features faded rapidly and could not be constrained by *NuSTAR* in observations a few days later, precluding a detailed study of its nature. One possible explanation for the origin of the reflected component was a funnel formed by a super-Eddington accretion flow, is often used to explain the spectra of ultraluminous X-ray sources (Margutti et al., 2019). Similar funnel-like geometries for super-Eddington accretion have been invoked in TDEs too (Kara et al., 2016; Dai et al., 2018, e.g.).

Due to its proximity and X-ray brightness, AT 2018cow is the only transient to show such a Compton reflection feature so far. With the greater sensitivity and improved target-of-opportunity capabilities afforded by *HEX-P*, studies of FBOTs will become more detailed and possible to larger distances and volume, allowing the determination of the central engine. We show a simulated *HEX-P* spectrum of AT 2018cow in Figure 6, compared to the *NuSTAR* actual data. We produced this by assuming the reflection + corona model (relxill + cutoffpl in XSPEC) described in (Margutti et al.,

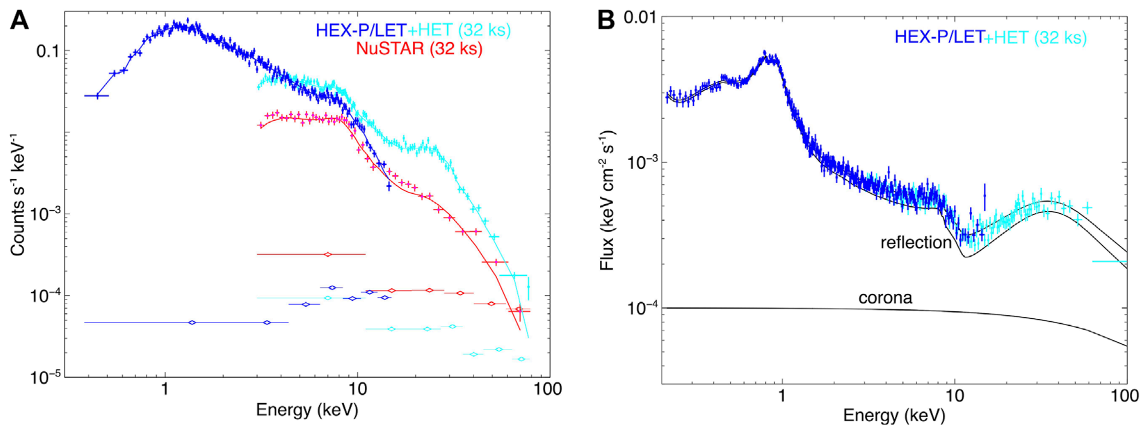

FIGURE 6
(A) A simulated spectrum of AT 2018cow with *HEX-P* compared to what *NuSTAR* observed (crosses). *HEX-P* would have detected the transient over the 0.2–80 keV range, which combined with greater effective area and lower background (diamonds) than *NuSTAR* would have allowed a detailed study of its spectral components. **(B)**. Unfolded *HEX-P* spectrum of AT 2018cow showing the reflection and corona components.

2019) with dimensionless spin parameter a = 0.7, X-ray spectral index $\Gamma = 1.0$, ionization parameter $\log\xi = 3.3$, iron abundance $A_{Fe} = 4.9$, high-energy cut off $E_{cut} = 170$ keV and reflection fraction $R_{refl} = -12$ as shown in the right panel of Figure 6 and with the same 32-ks exposure time as the *NuSTAR* observation. Not only will *HEX-P* provide the simultaneous soft X-ray data, it will provide a larger effective area and lower background than *NuSTAR* above 10 keV that will enable a more sensitive broadband X-ray spectral investigation of these sources, including detection of reflection components.

HEX-P will also be able to detect AT 2018cow-like events with a 10–30 keV signal-to-noise of 5 in a 20-ks observation up to 10 times further (600 Mpc), and in 1,000 times the volume, which will undoubtedly lead to a leap in understanding of these events.

4.4 Mapping the most extreme mass loss history of massive stars in interacting supernovae

Along with possible engine-powered optical transients like AT 2018cow, a plethora of supernovae types will be detected by upcoming optical surveys. These include interacting supernovae where the ejecta from the stellar explosion interact with the ISM, producing high-temperature shocked emission that can reveal the mass loss history of the massive star (Chevalier and Fransson, 2017). The high temperature of the shock can only be constrained with sensitive hard X-ray observations which have only been done with *NuSTAR* so far (Ofek et al., 2014; Chandra et al., 2015; Margutti et al., 2017b; Grefenstette et al., 2023, e.g., SNe 2010jli, 2014C and 2023ixf). For the case of SN 2014C at a distance of 14.7 Mpc, the shock produced bright hard X-ray emission that was observed with *Chandra* and *NuSTAR* (Margutti et al., 2017b). The hard X-ray coverage allowed for the measurement of the absorption and shock temperature (10–20 keV) as a function of time, which has only been achieved for SN 2014C so far. These data constrain the density profile of the environment of the supernova.

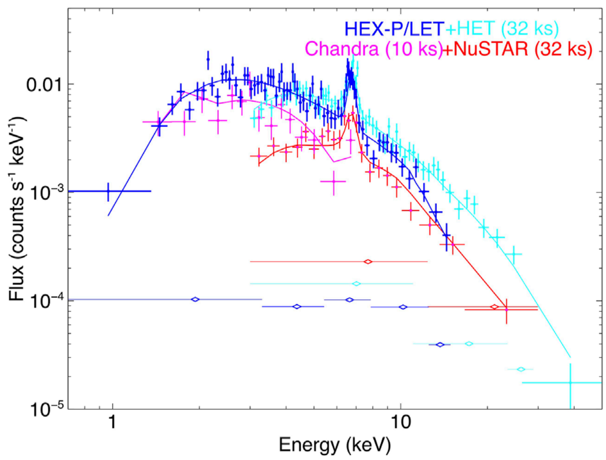

FIGURE 7
A simulated spectrum of SN 2014C with *HEX-P* compared to what *Chandra* and *NuSTAR* observed (crosses). *HEX-P* would have provided simultaneous data over the 0.2–50 keV range, which combined with greater effective area and lower background than *NuSTAR* (diamonds) would have provided a more detailed constraint on the shock properties.

Recently, *NuSTAR* observations of SN 2023ixf from 4 days post-explosion have provided the earliest constraints on the absorption and shock temperature to date (Grefenstette et al., 2023) and follow up observation promise to reveal more about the mass-loss history of its progenitor (Margutti et al. in prep.).

We show a simulated *HEX-P* spectrum of SN 2014C in Figure 7. We produce these spectra by assuming the absorbed thermal bremsstrahlung with Gaussian line component spectral model described in Margutti et al. (2017b) (`tbabs*bremss + gaussian` in XSPEC) with parameters $N_H = 3 \times 10^{22}$ cm^{-2} and $kT = 18$ keV with a 0.3–10 keV flux of 10^{-12} erg cm^{-2} s^{-1} and the same 32-ks exposure time as *NuSTAR*. Compared to *Chandra* and *NuSTAR*, *HEX-P* would have yielded a spectrum with signal-to-noise twice that of *NuSTAR* in the 3–30 keV band, providing better constraints on the shock temperature and absorption, where the uncertainties would be reduced by more than 50%. The spectral resolution of *HEX-P* at 6 keV is expected to be 0.14 keV, better than *NuSTAR* and similar to *Chandra*/ACIS. More importantly, *HEX-P* will also be able to detect SN 2014C-like events with a 10–30 keV signal-to-noise of 5 in a 20-ks observation up to 3 times further (45 Mpc), and in 27 times the volume.

As with binary neutron star mergers embedded in their ejecta, and AT 2018cow and SN 2014C like events, *HEX-P*'s hard X-ray sensitivity will be invaluable for studying explosive transients of all types that occur in dense environments. These may include high-redshift GRBs which are expected to occur in dense environments where optical and soft X-rays are likely to be obscured, but mid-infrared and hard X-rays can penetrate. For this reason there exists potential synergies between *HEX-P* and *JWST*.

4.5 Nuclear transients: Changing-look AGN, tidal disruption events and quasi-periodic eruptions

4.5.1 Changing look AGN

The advance of time-domain surveys is also revealing extreme variability in the accretion process onto supermassive black holes. Transient accretion events provide unique windows into the formation and evolution of accretion disks, the heating of the X-ray corona, and the connection between accretion and ejection via winds and jets. The X-ray band, in particular, is crucial to probing the innermost portions of the accretion flow, where strong outflows are launched and much of the gravitational energy is released.

Recently there has been a class of AGN discovered that undergo rapid transitions on timescales of months to years, in which broad lines either appear or disappear in the optical spectrum. These sources are known as changing-look AGN (CLAGN; for a recent review, see Ricci and Trakhtenbrot, 2022), and they challenge the classic unified model for AGN, whereby the presence of broad emission lines is solely a function of viewing angle. A particularly extreme source and the first CLAGN that was caught in the act of changing states, 1ES 1927 + 654 showed dramatic and unprecedented X-ray variability as optical broad lines formed (Trakhtenbrot et al., 2019; Ricci et al., 2020). Shortly after the optical outburst, the canonical X-ray corona was destroyed (Ricci et al., 2020). Extensive X-ray monitoring revealed its reappearance, allowing for one of the first studies of how an AGN corona is formed (Ricci et al., 2021; Masterson et al., 2022). This dramatic behavior has been explained by either a TDE occurring in an AGN (Ricci et al., 2020) or an inversion in the magnetic flux polarity (Scepi et al., 2021; Laha et al., 2022). *NuSTAR* observations were crucial for disentangling the soft photon index and low cutoff energy as the corona formed, while softer instruments like *XMM-Newton* and *NICER* probed the evolution of the inner accretion flow in 1 ES 1927 + 654, including rapid variability of the soft X-ray flux and a relativistic outflow launched from the inner disk (Masterson et al., 2022). Thus, broad energy coverage in the X-ray band is crucial to fully understanding this and other CLAGN. With its 0.2–80 keV bandpass, *HEX-P* will be uniquely situated to probe the X-ray evolution, variability, and coupling between the inner disk and the corona in CLAGN.

4.5.2 Tidal disruption events

TDEs also hold key insights into how the X-ray corona is powered and formed, as numerous TDEs have shown spectral hardening and the formation of a corona at late-times (~ a few years after the initial disruption; e.g., Wevers et al., 2021; Yao et al., 2022; Guolo et al., 2023). They can also serve as probes of extreme accretion, as dramatic X-ray spectral variability, similar to that of 1ES 1927 + 654, has also been seen in TDE candidates (e.g., a repeating TDE discovered by eROSITA, which shows a repetitive creation and collapse of the X-ray corona; Liu et al., 2023).

Likewise, as TDEs can also transition from super-to sub-Eddington as the mass fallback rate drops, *HEX-P* can also be used to study the disk-corona connection during these transitions, thereby allowing for comparisons to state transitions in black hole binaries (Remillard and McClintock, 2006) and tests of the scale-invariant nature of accretion. Moreover, X-ray observations of TDEs can help illuminate the underlying accretion disk evolution, which is especially hard to probe with optical emission alone.

X-rays from TDEs also serve as an independent way of measuring black hole mass and spin, but this is currently quite difficult to do with existing facilities. Detailed X-ray spectral modeling of the thermal continuum emission in TDEs can provide constraints on the mass and spin of the black hole (e.g., Wen et al., 2020). However, there are inherent uncertainties related to the presence of an X-ray corona, which can introduce biases. Likewise, the detection of X-ray quasi-periodic oscillations (QPOs) can be used to constrain the black hole spin (e.g., Pasham et al., 2019), but are difficult to detect with low count rates and short observations. Finally, through time-lags between the continuum and reflected components, Fe Kα reverberation mapping provides constraints on the disk and coronal geometrics, as well as black hole spin in systems with geometrically thin disks truncated at the ISCO. To date, only one source, the relativistically jetted TDE Swift J1644, has shown an Fe Kα reverberation signal, potentially due to the fact that the corona often appears at late times in TDEs when the emission becomes faint (Kara et al., 2016). With its high throughput, good spectral energy resolution, low background, and ability to do long pointed observations, *HEX-P* studies of TDEs will advance all three of these techniques for measuring BH mass and spin. These studies will add invaluable constraints on the demographics of quiescent, low-mass SMBHs, which are not readily available through other means.

Theoretical studies of TDEs have proposed that the apparent X-ray/optical dichotomy among TDEs is a result of viewing angle dependence (Dai et al., 2018), which has been recently supported by *Swift* and *XMM-Newton* observations of numerous optically-selected TDEs (e.g., Guolo et al., 2023). *HEX-P* will be able to provide frequent and systematic X-ray follow-up of optically-selected TDEs, which are expected to become far more numerous in the next decade (e.g., Bricman and Gomboc, 2020). This is vital for understanding sample biases, as well as probing other interesting accretion phenomena, such as the fraction of TDEs that can launch powerful outflows and their evolution over time, as well as the physical conditions that are required to launch them.

Finally, TDEs are also powerful probes of relativistic and multi-messenger astrophysics, with powerful on-axis jets detected in a few sources (Burrows et al., 2011; Cenko et al., 2012; Andreoni et al., 2022; Pasham et al., 2023) and recent discoveries of high-energy neutrinos coincident with three optical TDE candidates (contributing a sizeable fraction of the astrophysical high-energy neutrino flux, despite being found in non-jetted systems; e.g., Stein et al., 2021; van Velzen et al., 2021; Reusch et al., 2022). Probing future jetted and neutrino-emitting TDEs in the X-ray band with *HEX-P* will help to disentangle particle acceleration mechanisms and models for both jet and neutrino production.

4.5.3 Quasi-periodic eruptions

A recently discovered phenomenon whose origins remain elusive are quasi-periodic eruptions (QPEs) of nearby low mass galaxies (e.g., Miniutti et al., 2019; Giustini et al., 2020; Arcodia et al., 2021; Chakraborty et al., 2021; Guolo et al., 2023). With recurrence times between 2 h and ~22 days, potential explanations range from rapid limit-cycle oscillations in the inner accretion disk of an AGN, to various flavors of stellar mass companions on a bound orbit about a massive black hole. While the discovery of new systems requires a large area survey, detailed follow-up studies with *HEX-P* can help to further constrain their trigger mechanism by accurately measuring their X-ray properties and evolution over time. In particular, the presence and role of the X-ray corona remains unclear in the known sources and our current knowledge is limited by the effective area of existing telescopes (taking into account the sharp decrease in signal of QPEs at >1 keV energies). The high throughput and low background of *HEX-P* would enable more detailed constraints on the behaviour of the >1 keV energy emission in QPEs, while its high throughput down to 0.2 keV will allow for efficient photon collection compared to existing missions, as this is where the QPE emission peaks.

HEX-P will make significant contributions to our understanding of extreme accretion physics in these nuclear transients, including improving key constraints on the evolution of coronal parameters like Γ and E_{cut} by a factor of ~2 with respect to *XMM-Newton* and *NuSTAR* (Kammoun et al., 2023). More details on the coronal physics that we can glean from these transients with *HEX-P*, as well as SMBH coronal physics in general, are described in Kammoun et al. (2023). Separately, Connors et al. (2023) describe the coronal physics of accreting stellar-mass BHs.

4.6 Blazars

Many AGN are known to launch relativistic jets which can extend up to kiloparsecs in length. These jets emit across the electromagnetic spectrum (radio to γ-ray) and are also multi-messenger (neutrino) emitters. When the viewing angle is close to on axis (viewing angles, $\theta_V < 5°–10°$) we observe a blazar, while at larger viewing angles we classify them as misaligned AGNs or radio galaxies (e.g., Urry and Padovani, 1995; Hovatta et al., 2009).

Blazars are believed to be able to accelerate protons to very high energies. This was potentially confirmed by the claimed association of the γ-ray flaring blazar TXS 0506 + 056 with the IceCube neutrino event IceCube-170922A (Aartsen et al., 2018). In order to probe the transition between the synchrotron and high-energy emission part of the spectrum, where signatures of electromagnetic cascades associated with the neutrino-producing photo-hadronic interactions should emerge (Murase et al., 2018a) simultaneous broadband coverage from X-ray to MeV γ-rays is required, and has so far been lacking. This was shown in previous studies of a previous neutrino flare potentially linked to TXS 0506 + 056 where the lack of sensitive simultaneous broad-band X-ray spectral and temporal coverage did not allow for any conclusion on the emission mechanism (e.g., Reimer et al., 2019; Zhang et al., 2020). Simultaneous broadband coverage of neutrino alerts in the direction of blazar sources could be the tipping point for jet models as well as confirming AGN as one of the sources of high-energy cosmic rays.

For the first time *HEX-P* will allow us to detect the spectral signatures that will conclusively yield the preferred high-energy emission mechanisms in jets, and, by extension, their composition. Furthermore, combined with current and upcoming observatories such as COSI, IXPE, CTA, IceCube Gen 2, *HEX-P* will reveal the preferred particle acceleration and emission mechanism of the brightest objects in the Universe, fulfilling the promises of multi-wavelength and multi-messenger science. The contribution to blazar science by *HEX-P* is described in more detail in Marcotulli et al. (2023).

4.7 Fast radio bursts

Fast Radio Bursts (FRBs) are millisecond duration transients discovered through their luminous sweeps in multi-band radio detectors (Petroff et al., 2019). Initially, FRBs were thought of as non-recurrent phenomena. However in the last decade advent of radio facilities such as MeerKAT, MeerTRAP and CHIME which could regularly monitor the known population of FRBs have led to a deluge of fast radio burst transients spanning a wide range of the parameter space. While most of the ~10^3 FRBs detected so far do not seem to repeat yet, 24 of them have occasionally shown high burst rates clustered over a short duration. The emission models for both non-repeating and repeating FRBs are not yet well-constrained.

In a breakthrough discovery, observational evidence for the magnetar model as a source of FRBs occurred on 2020 April 28, when an FRB-like radio burst was detected from the Galactic magnetar SGR 1935 + 2,154 (Andersen et al., 2020; Bochenek et al., 2020), in the winding hours of a major burst storm (Younes et al., 2020); it had a fluence rivaling those of the faint end of extragalactic FRBs. Moreover, the FRB occurred simultaneously with a bright, short X-ray burst, hence, relating it to magnetar activity and providing crucial evidence for its triggering mechanism (e.g., Mereghetti et al., 2020; Li et al., 2021; Ridnaia et al., 2021).

The discovery of FRB-like bursts from magnetars opened up new avenues for the study of extragalactic FRBs (e.g., Wadiasingh and Timokhin, 2019). This discovery opened up new questions such as 1) What is unique about the FRB-associated X-ray bursts, and why do the majority of X-ray bursts lack a radio counterpart? 2) What is the distribution of the spectral properties for FRB-associated X-ray bursts? Are their distinctive spectral properties universal across radio fluence? 3) Is the radio to X-ray flux ratio (L_R/L_X) constant for all FRB-like radio bursts? 4) What is the radio-X-ray time-lag across burst fluence? Answering these questions will require 1) a broad X-ray coverage given that the spectral energy distribution of magnetar burst peaks in the 20–30 keV range, 2) high timing resolution (≲ 1 ms) for accurately measuring the radio-X-ray lag in burst arrival time (Mereghetti et al., 2020), 3) sensitivity to faint X-ray bursts, i.e., fluence $<10^{-7}$ erg cm^{-2}, to sample a large fraction of the X-ray and radio burst fluence distribution given their steep shapes ($N \propto S^{-0.6}$, Younes et al., 2020). *HEX-P* is the only facility to satisfy all the above criteria. The contribution to FRB science by *HEX-P* is described in detail in Alford et al. (2023).

5 Conclusion

The 2030s will be an exciting era for time domain and multi-messenger astronomy, with a veritable orchestra of new facilities providing new views of new events in the Universe. We are virtually guaranteed to discover events that are barely dreamed of currently. Given this evolving landscape, it is essential that a sensitive, versatile, and flexible X-ray observatory will be available in the 2030s, able to do broadband X-ray studies, including imaging, spectroscopy, and timing, to understand the nature and the physics of these events. From the early days of X-ray astronomy, it was revealed that the high-energy sky is highly variable–and that X-rays provide a powerful and essential tool for understanding the range of phenomena. This paper describes how *HEX-P* will provide that needed capability for the 2030s.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://heasarc.gsfc.nasa.gov/db-perl/W3Browse/w3browse.pl.

Author contributions

MB: Writing–original draft, Writing–review and editing. RM: Writing–review and editing. AP: Writing–review and editing. AJ: Writing–review and editing. KH: Writing–review and editing. JA: Writing–review and editing. GH: Writing–review and editing. EK: Writing–review and editing. KuM: Writing–review and editing. MM: Writing–review and editing. LM: Writing–review and editing. AR: Writing–review and editing. GY: Writing–review and editing. DS: Writing–review and editing. JG: Writing–review and editing. KrM: Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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