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

White Paper for Probe-Class Astrophysics Mission Concept

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Summary: The *High-Energy X-ray Probe (HEX-P)* is a probe-class (~$500M) next-generation high-energy X-ray observatory with broadband (2-200 keV) response and ~40 times the sensitivity of any previous mission in the 10-80 keV band, and >500 times the sensitivity of any previous mission in the 80-200 keV band. Intended to launch contemporaneously with *Athena, HEX-P* will provide fundamental new discoveries that range from resolving ~90% of the X-ray background at its peak, to measuring the cosmic evolution of black hole spin, to studying faint X-ray populations in nearby galaxies. Based on *NuSTAR* heritage, *HEX-P* requires only modest technology development, and could easily be executed within the next decade.

We describe the *High-Energy X-ray Probe (HEX-P*; Harrison et al. 2011), a probe-class mission that will provide the natural successor to the *Nuclear Spectroscopic Telescope Array* Small Explorer (*NuSTAR*; Harrison et al. 2013), with a factor of ~40 gain in sensitivity and covering a wider bandpass. *HEX-P* is highly complementary to *Athena*, which emphasizes high-resolution spectroscopy and imaging below 10 keV. *HEX-P* achieves this with the larger effective area afforded by a Falcon 9 launch vehicle (compared to *NuSTAR*'s Pegasus launch vehicle). This allows three grazing incidence optics modules, each comprised of 390 shells, compared to *NuSTAR*'s two modules comprised of 133 shells. Combined with improvements in the optical designs and mirror mounting, *HEX-P* will have high spatial resolution (15″ half-power diameter; 4 times better than *NuSTAR*) and a broad energy coverage (2-200 keV; Figure 1 and Table 1). *HEX-P's* photon-counting detectors also offer timing resolution at the 0.1 msec level with count rate handling to 10^3 Hz. The mission will launch into a circular low-Earth orbit with near-equatorial inclination. Our rough order-of-magnitude (ROM) cost is $500M, including launch and 5 years of operations. *HEX-P* is intended to operate primarily as an point-and-stare observatory, with a funded, competitive Guest Observer program. All key *HEX-P* mission elements have strong *NuSTAR* heritage, with only modest technology development required. The mission could easily be executed within the next decade.

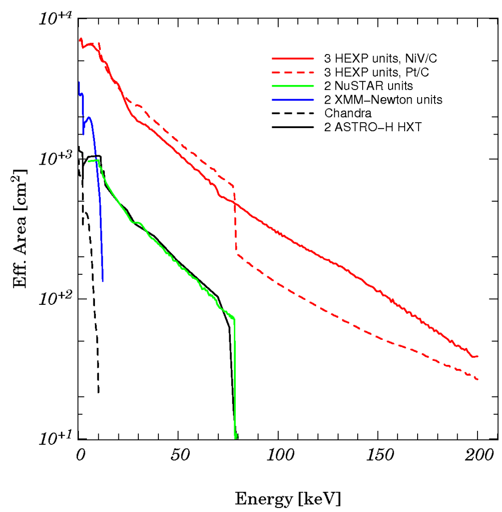

Figure 1. Effective area vs. energy for *HEX-P* and current/near-term focusing missions. We plot two potential recipes for the *HEX-P* mirror coatings: Pt/C is the recipe currently used by *NuSTAR*, while NiV/C would require some modest development.

The combination of wide bandpass and high-energy sensitivity will allow *HEX-P* to revolutionize our understanding of both Galactic and extragalactic black holes in the Universe, achieving science that cannot be done with existing or currently planned facilities. If developed and launched on a similar timescale to *Athena*, *HEX-P* would support simultaneous observations, greatly enhancing *Athena*'s ability to, for example, understand the detailed physics of black hole accretion and hot, merger-driven shocks in clusters — both systems have continua extending to high energy that must be properly modeled to interpret their spectra. The broad-band continuum measurements performed by *HEX-P*, both on their own and in conjunction with *Athena*, are critical for key Physics of the Cosmos (PCOS) science objectives: *When and how did supermassive black holes grow?, What happens close to a black hole?,* and *How does large scale structure evolve? HEX-P* will also address a broad range of additional objectives, from studying binary populations in nearby galaxies to understanding the mechanisms that drive supernova explosions. In particular, as a natural follow-on to *NuSTAR*, *HEX-P* addresses science that is not planned by any flagship-class missions, and is beyond the capability of an Explorer-class mission. *HEX-P* science is clearly in the realm of a Probe-class mission.

Parameter	*HEX-P*	*Athena (X-IFU)*	*NuSTAR*
bandpass	2 - 200 keV	0.3 - 12 keV	3 - 79 keV
angular resolution [HPD]	15″	5″	58″
spectral resolution [FWHM]	250 eV @ 6 keV 600 eV @ 60 keV 1 keV @ 122 keV	2.5 eV @ 6 keV	400 eV @ 6 keV 900 eV @ 60 keV
timing resolution	0.1 msec	—	0.1 msec
field of view	13′ × 13′	5′ × 5′	12′ × 12′

Table 1. Key performance parameters.

Black Hole Growth over Cosmic Time. A complete census of AGN activity is the backbone behind any attempt to understand the mass accretion history of the universe, and the relationship between accretion and star formation. Deep surveys with *Chandra* and *XMM-Newton* resolve only ~75% of the 6-10 keV background and are missing the vast majority of the most heavily obscured AGN ($N_H > 3\times10^{23}$ cm^{-2}). Importantly, models suggest that the most heavily obscured AGNs represent a key early and rapid black hole growth phase. Sensitive mid-IR observations and stacking analyses from deep X-ray surveys imply that the space density of heavily obscured AGNs is large (e.g., Stern et al. 2005, Treister et al. 2010) while theoretical models suggest that they represent a growth phase that is qualitatively different from less obscured AGN. However, we currently lack definitive measurements of their space density and properties. Observations with *NuSTAR* now directly resolved ~35% of the background at its ~20 keV peak (Harrison *et al.* 2016), but are unlikely to significantly surpass this level given issues of sensitivity and source confusion. With its 4× improvement in resolution and order-of-magnitude increase in effective area, *HEX-P* will extend this science with significant samples of heavily obscured AGN out to high redshift, uncovering new AGN source populations and resolving ~90% of the X-ray background at its peak.

Black Hole Accretion Physics. X-ray observations of AGN above 10 keV provide a critical complement to the more standard 0.5-10 keV window, allowing more precise constraints to be placed on the physical properties of the black hole, corona, and accretion disk. As demonstrated by *NuSTAR*, studies that extend beyond 10 keV provide the most robust measurements of black hole spin (*e.g.*, Risaliti *et al.* 2013), as well of the temperature and structure of the X-ray emitting corona (*e.g.*, Fabian *et al.* 2015 and references therein). However, *NuSTAR* is unlikely to provide spin measurements for more than a few dozen local Seyfert galaxies, and the coronal measurements are based on subtle continuum downturns at ~50 keV used to infer cut-off temperatures of ~100 keV and higher. *HEX-P* will be revolutionary in these regards, providing robust black hole spin measurements for statistically significant samples of objects over a range of luminosities, out to cosmological distances. *HEX-P* will also provide robust measurements of high-energy spectral cut-offs, which probe the temperature and geometry of the poorly understood corona. In addition, broad-band high-energy campaigns will probe whether the corona is outflowing and/or extended (*e.g.*, Zoghbi *et al.* 2014, Wilkins & Gallo 2015). Though a model in which the corona is an atmosphere to the inner accretion disk is still viable, many of the *NuSTAR* observations to date are well described by the so-called "lamppost model", which considers the corona to be a compact source that can move along the spin axis of the black hole (e.g., Parker *et al.* 2014). While *NuSTAR* has begun such investigations for the nearest, brightest Seyferts, *HEX-P* will characterize the corona over a broad range of black hole mass and accretion rate, reaching out to cosmological distances.

Other Objectives. With its revolutionary increase in sensitivity, *HEX-P* will be an extremely capable and flexible platform, enabling a broad suite of additional science programs. For example, *HEX-P* will extend hard X-ray studies of the local universe to fainter levels, enabling the identification (rather than simple detection) of large numbers of compact objects (*e.g.,* black holes, neutron stars, ultraluminous X-ray sources, and white dwarfs) in our Galaxy and nearby galaxies. By studying regions with different star formation rates, metallicities, and ages, *HEX-P* will provide unique information on the how star formation proceeds in different environments. As one other example, *HEX-P* will be sensitive to the 158 keV ^{56}Ni line in supernovae, as well as Compton-scattered continuum from higher energy γ-ray lines. *HEX-P* will be sensitive to SNe Ia within ~70 Mpc, corresponding to a supernova rate of ~40 per year. The flux and spectral shape of the γ-ray line and hard X-ray continuum are sensitive to both the overall nucleosynthesis and the amount of mixing in the ejecta, allowing us to address fundamental questions about supernovae, from their progenitor systems to how the nuclear flame propagates.

References • Fabian *et al.* 2015, MNRAS, 451, 4375 • Harrison *et al.* 2011, http://pcos.gsfc.nasa.gov/studies/rfi/Harrison-Fiona-RFI.pdf • Harrison *et al.* 2013, ApJ, 770, 103 • Harrison *et al.* 2016, ApJ, submitted (arXiv:1511.04183) • Parker *et al.* 2014, MNRAS, 443, 1723 • Risaliti *et al.* 2013, Nature, 494, 449 • Stern *et al.* 2005, ApJ, 631, 163 • Treister *et al.* 2010, ApJ, 722, 238 • Wilkins & Gallo 2015, MNRAS, 449, 129 • Zoghbi *et al.* 2014, ApJ, 789, 56