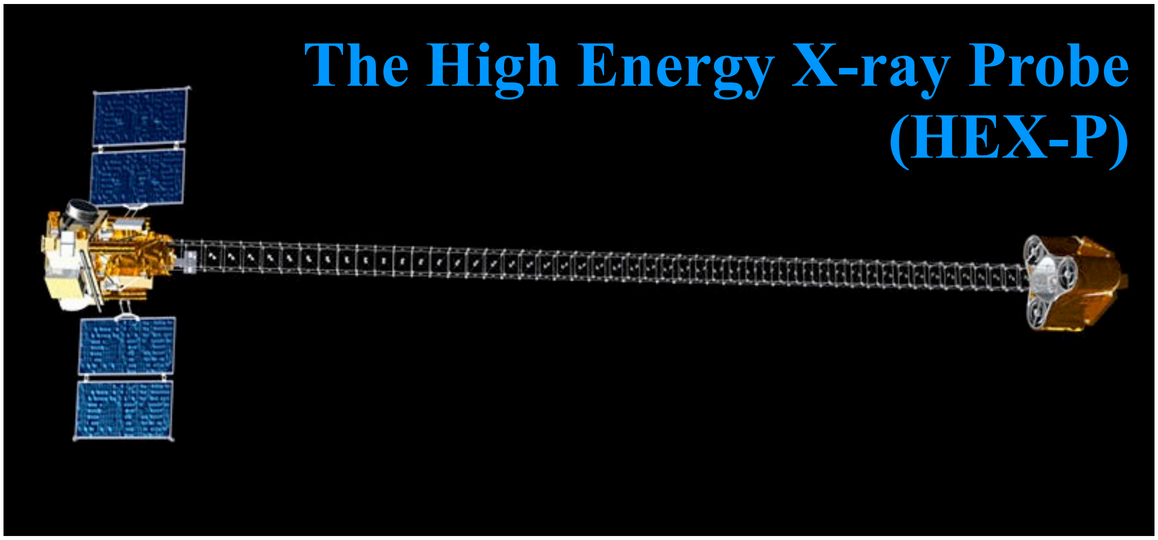
The High Energy X-ray Probe (HEX-P)



Mission Concept White Paper for Next NASA X-Ray Astronomy Mission

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Brief Description:

The *High Energy X-ray Probe (HEX-P)* is a concept for a probe-class (~$480M) next-generation high-energy X-ray mission with broadband (0.1-200 keV) response and ~40 times the sensitivity of previous missions above 10 keV. Intended to launch contemporaneously with *ATHENA, HEX-P* recovers many of the key science objectives *IXO* lost when the high-energy capabilities of that mission were de-scoped to create *ATHENA*. In addition to joint observations with *ATHENA*, *HEX-P* will be an extremely powerful facility with an exciting scientific agenda of its own. *HEX-P* will provide fundamental 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 binary populations in nearby galaxies. Based on *NuSTAR*, *XMM-Newton* and *eROSITA* heritage, *HEX-P* requires only modest technology development, and could easily be executed within the next decade.

1. Introduction

The de-scoping of the *International X-ray Observatory (IXO)* to ESA's *Advanced Telescope for High Energy Astrophysics (ATHENA)* resulted in the loss of a key capability: the extension of sensitivity into the hard X-ray band ($E \geq 10$ keV). *IXO*'s Wide-Field Imager (WFI) + Hard X-ray Imager (HXI) combination would have covered the 0.1 to 40 keV band with spectral resolution ΔE=150 eV @ 6 keV and 1 keV @ 20 keV. The re-scoped *ATHENA* currently includes only a high-resolution spectrometer and WFI, with no planned extension to high energy. While ESA's M-class *Large Observatory for X-ray Timing (LOFT)* concept will, if selected, carry out the neutron star timing studies envisioned for *IXO*, no planned mission will replace the broad response at high sensitivity extending into the hard X-ray band which is so critical to achieving *IXO*'s key objectives.

Here, we describe the *High Energy X-ray Probe (HEX-P)*, a probe-class (ROM cost $480M) mission that will not only replace *IXO's* hard X-ray capability, but by optimizing the optics design for high energy and widening the bandpass, *HEX-P* will provide an extremely powerful observatory with an important scientific agenda of its own. *HEX-P* (Table 1) is the natural successor to the *Nuclear Spectroscopic Telescope Array* Small Explorer (*NuSTAR*; Harrison *et al.* 2010 – launch in March 2012). The *HEX-P* gains in hard-band sensitivity parallel the leap in soft X-ray spectroscopic performance that will be made by *ATHENA* relative to the *Astro-H* X-ray Calorimeter Spectrometer (launch mid-2013). Many of *NuSTAR's* observations (5-80 keV) require simultaneous *XMM-Newton* or *Suzaku* coverage; *HEX-P* covers the combined *XMM-NuSTAR* bandpass (0.15-200 keV) by including a combination Silicon/CdTe active pixel sensor. *HEX-P's* effective area is a factor of three larger than *XMM's* (0.1-10 keV) and a factor of seven larger than *NuSTAR*'s (Fig. 1). The sensitivity advance relative to *NuSTAR* is

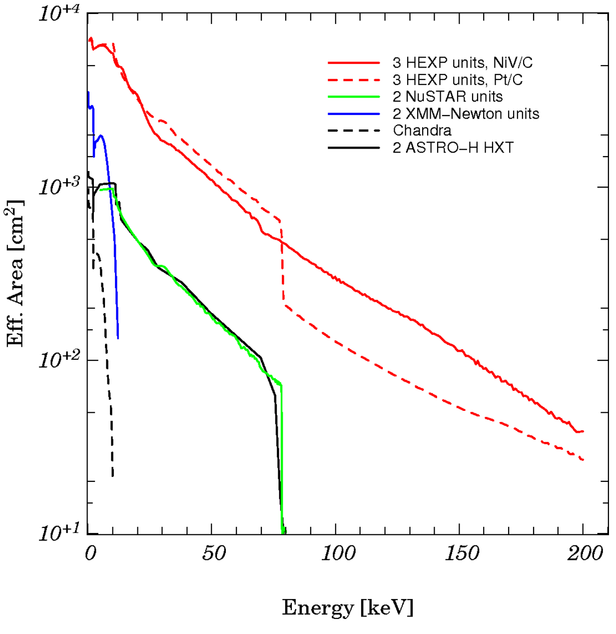

Figure 1. Effective area vs. energy for *HEX-P* and current/near-term focusing missions. We plot two potential recipes for the *HEX-P* mirror coatings: Pt/C is the recipe currently used by *NuSTAR*, while NiV/C would require some development.

a factor of ~40 and the factor relative to *Astro-H*/HXI is ~100. *HEX-P's* photon-counting detectors offer time resolution at the 0.1 msec level with count rate handling to 10^3 Hz.

Table 1. Key performance parameters.

Parameter	*IXO* (HXI+WFI)	*HEX-P*	*ATHENA* (XMS)	*NuSTAR*
bandpass	0.1 - 40 keV	0.15 - 200 keV	0.1 - 10 keV	5 - 80 keV
angular resolution [HPD]	5″ (3 - 7 keV) 30″ (7 - 40 keV)	10″ - 15″	10″	50″
spectral resolution [FWHM]	150 eV @ 6 keV 1.5 keV @ 60 keV	150 eV @ 6 keV 1.5 keV @ 60 keV	3 eV @ 6 keV	600 eV @ 6 keV 1.2 keV @ 60 keV
timing resolution	1.3 msec	0.1 msec	—	—
field of view [FWZI]	18′ × 18′ (0.1 - 15 keV)	13′ × 13′ (0.1 - 100 keV)	2.4′ × 2.4′	13′ × 13′

As described below, 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. If developed and launched on a similar timescale to *ATHENA*, *HEX-P* would support simultaneous observations with *ATHENA*, 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 line spectra). The broad-band continuum measurements performed by *HEX-P*, both on their own and in conjunction with *ATHENA*, are critical for three key *IXO* science objectives: *What happens close to a black hole?, When and how did supermassive black holes grow?* and *How does large scale structure evolve?* As detailed below, *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.

2. Science Objectives

2.1. Black Hole Growth Over Cosmic Time

IXO Key Objectives addressed: When and how did supermassive black holes grow? and What is the connection between supermassive black hole formation and evolution of large-scale structure?

The construction of a complete census of active galactic nuclei (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. With a complete census we can determine how black holes grow across cosmic time and reveal connections between the host galaxy and larger scale environment on the fueling of the black hole. However, the formidable barrier that must be overcome in this quest is the presence of dust and gas in the regions around the AGN, which obscures the growing black hole and requires penetrating observations to unambiguously reveal AGN signatures. Deep surveys with *Chandra* and *XMM-Newton* have provided the most penetrating probe of distant AGN activity to date (see Brandt & Alexander 2010 for a recent review). However, there is unequivocal evidence that these surveys resolve only ~50-70% of the 6-10 keV X-ray background and are missing the most heavily obscured AGN ($N_H > 3\times10^{23}$ cm^{-2}; Worsley *et al.* 2005, Luo *et al.* 2011). The directly resolved fraction of the background at its ~30 keV peak from current surveys is only ~2%, with very few sources identified at redshift z>0.1 (*e.g.,* Ajello *et al.* 2008). Observations with *NuSTAR* are expected to increase the resolved fraction to ~30% (Ballantyne *et al.* 2011). Models suggest that the most heavily obscured AGNs represent an important early and rapid black hole growth phase (*e.g.,* Hopkins *et al.* 2006), and therefore their identification is more than just a simple bookkeeping exercise — without having observations sensitive to their identification we may miss a crucial black hole growth phase.

Consistent with models of the X-ray background, both stacking analyses from deep X-ray surveys and less obscuration-sensitive mid-IR surveys show that the space density

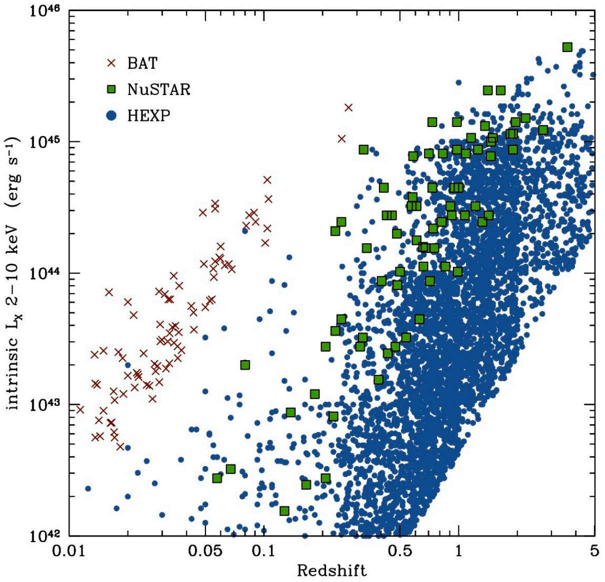

Figure 2. *HEX-P* will detect >40 times as many AGN as *NuSTAR* in the same survey exposure time, clearly identifying the origin of the cosmic X-ray background. Plotted is the predicted redshift-luminosity plane for AGN detected in deep (6.2 Ms) surveys tiling one deg^2 with *NuSTAR* and *HEX-P*. Also plotted are 100 random AGN detected by *Swift*/BAT (Tueller *et al.* 2010). While *NuSTAR* is expected to detect only ~100 sources at 10-30 keV, *HEX-P* should detect ~4000 sources.

of distant, heavily obscured AGN is large, outnumbering the less heavily obscured AGN population (*e.g.,* Stern *et al.* 2005; Treister *et al.* 2010). However, significant differences exist between current models in terms of the fraction of the X-ray background that is attributable to Compton-thick AGN, and how that fraction depends on redshift and luminosity. Direct detections of the most heavily obscured AGN at X-ray energies have been rare thus far. *NuSTAR* will provide the first breakthrough for this science by selecting AGN largely independent of absorption across a broad range of the luminosity-redshift plane (Fig. 2). *HEX-P* will extend this science with significant samples out to high redshift, uncovering new source populations and resolving >90% of the X-ray background at its peak.

2.2. **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 continuum and accretion disk. Approximately 40% of AGN show broadened, skewed emission-like features centered at a rest-frame energy of 6.4 keV (Nandra *et al.* 2007; de la Calle Perez *et al.* 2010), along with prominent "bumps" above 10 keV, peaking from 20-30 keV and falling off in flux thereafter. The prevailing interpretation identifies these features as signatures of reflection from the inner accretion disk, *i.e.,* an Fe Kα line and Compton hump. This emission arises when the surface layers of the disk are irradiated by Comptonized photons scattered downwards by high-energy electrons in the putative "corona" (*e.g.*, George & Fabian 1991), producing a series of fluorescent emission lines, of which Fe Kα is the most prominent due to its abundance, high energy and high fluorescent yield. Fe K absorption at 7.1 keV shapes the low-energy end of the Compton hump, while Compton down-scattering of these reflection spectrum photons by the gas in the disk at higher energies (>30 keV) completes its shape.

IXO Key Objectives addressed: When and how did supermassive black holes grow? and What happens close to a black hole?

Doppler broadening and relativistic effects will be imposed on the resulting features, with the reflection spectrum broadened and skewed in a characteristic fashion as determined by the magnitude and direction of the spin (see review in Reynolds & Nowak 2003). One can then constrain the angular momentum of the black hole by correctly modeling the reflection spectrum, especially the morphology of the broadened iron line (*e.g.,* Brenneman & Reynolds 2006). In dimensionless units, the spin parameter a is defined as $a \equiv cJ/GM^2$, where J is the angular momentum of the black hole, M is its mass, and c and G are the speed of light and Newton's constant, respectively ($-1 \leq a \leq 1$).

Critical to black hole spin measurements are simultaneous high spectral resolution observations of the Fe Kα emission complex at low energies and sensitive observations at higher energies to constrain the continuum. In particular, measuring the continuum shape at high energies breaks the degeneracy between absorption and reflection, which is essential for an accurate spin measurement. There are currently only eight supermassive black hole spins that have been robustly measured and published. *NuSTAR* can expand this number to a few dozen sources. Notably, these will be challenging observations to organize as they require coordinated, simultaneous observations by both *NuSTAR* and a sensitive, low-energy facility such as *XMM-Newton*. With more collecting area than any current X-ray mission and simultaneous coverage across the full 0.15-200 keV window, *HEX-P* will be able to do this science at cosmological distances, measuring precise ($\Delta a = 0.1$) black hole spin constraints in a statistically significant sample of AGN (*e.g.,* Fig. 3). This will enable us to infer the mechanism of growth of these black holes during their most recent epoch of evolution, yielding insights into how black holes and their host galaxies form and evolve (*e.g.,* Berti & Volonteri 2008).

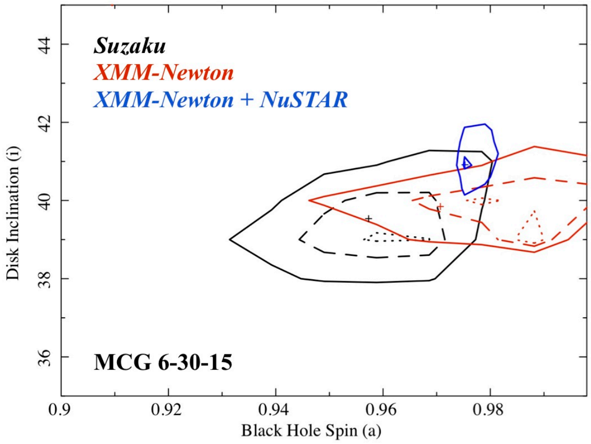

Figure 3. Predicted precision with which *NuSTAR* will measure the black hole spin of MCG 6-30-15 in a 150 ks observation, compared to current facilities. *HEX-P* will allow similar precision for systems 25× fainter.

HEX-P will also be revolutionary in terms of directly measuring the high-energy spectral cut-off, thereby constraining the temperature and structure of the corona. Most AGN are expected to have high-energy cut-offs above 100 keV, so while *NuSTAR* can constrain spectral curvature associated with this cut-off, *HEX-P* will make direct cut-off measurements. Current observations suffer from a degeneracy between two key coronal parameters, temperature and optical depth. *HEX-P* will break that degeneracy, furthermore allowing us to probe the coronal geometry (*e.g.,* plane-parallel, patchy active regions spread along the disk *vs.* a sphere/cylinder inside some critical disk radius). By selecting objects with a range of black hole mass and/or accretion rates, we will address how these properties affect the corona parameters (temperature, optical depth), thereby improving our understanding of the physics of black hole accretion. Determining the light curve of each spectral component and measuring energy-dependent time lags, *HEX-P* will also study feedback between the emitting regions with unprecedented detail.

IXO Key Objectives addressed: How does large-scale structure evolve?

2.3. **Galaxy Clusters**

All observational evidence as well as numerical simulations indicate that clusters form via mergers of sub-clusters, or accretion of smaller structures into a more massive cluster: this is the commonly accepted “hierarchical clustering” scenario. Intrinsic to the process of cluster growth through both merging and accretion is the formation of shocks that accelerate particles to relativistic energies (*e.g.,* Fujita & Sarazin 2001). The spatial and energy distribution of such particles traces the velocity and geometry of mergers. Measurements of non-thermal components are therefore an important route to advancing understanding of cluster growth, and thermalization of the X-ray emitting gas. Relativistic particles also provide an additional pressure component which needs to be accounted for in mass determination (*e.g.,* Pfrommer *et al.* 2008), both in the analysis of the X-ray data, but also in

Sunyaev-Zeldovich studies. Mass determinations are, of course, central to using the growth of clusters to constrain cosmology.

The distribution of shock-accelerated particles can be determined in the low-frequency radio where they emit synchrotron radiation, and also in the hard X-ray where they up-scatter microwave background photons (in soft X-ray band non-thermal emission is typically swamped by thermal radiation from the intracluster gas). Combining radio and hard X-ray data allows direct measurement of the magnetic field, which also traces the cluster formation history. Previous high-energy observations have been inconclusive owing to systematic effects associated with background subtraction inherent to non-imaging instruments (*e.g.,* Ajello *et al.* 2010). While *NuSTAR* will make pioneering observations of a few clusters, the high-energy response and sensitivity of *HEX-P* is essential for extending observations to a large sample, and enabling maps to be made of the intracluster magnetic field. This will enable conclusions to be drawn about the past merger and accretion history. Specifically, accretion results in a significantly different particle spatial and spectral distribution than mergers (Fujita & Sarazin 2001).

Combined observations with X-ray spectroscopy missions are also important in unraveling cluster evolution, particularly the accretion history. High resolution spectroscopy provides information about the kinematics of the accreting gas. Hard X-ray studies, in conjunction with the low-frequency radio observations, will be key in determining the distribution of non-thermal particles and the structure of the shocks expected to form in the accretion process. The joint analysis of the radio, soft X-ray spectroscopy, and hard X-ray data will be able to reveal the structure of the accretion shocks, answering questions such as: *What is their Mach number?, Is the magnetic field compressed during the shock formation, as is likely the case for supernova remnants?* and *Do we have any evidence of acceleration of protons, and thus any indication of origin of energetic cosmic rays in clusters of galaxies? HEX-P's* sensitivity will allow studies of an appreciable number of clusters, both those undergoing major mergers and those coalescing from the smaller fragments/filaments forming the cosmic web.

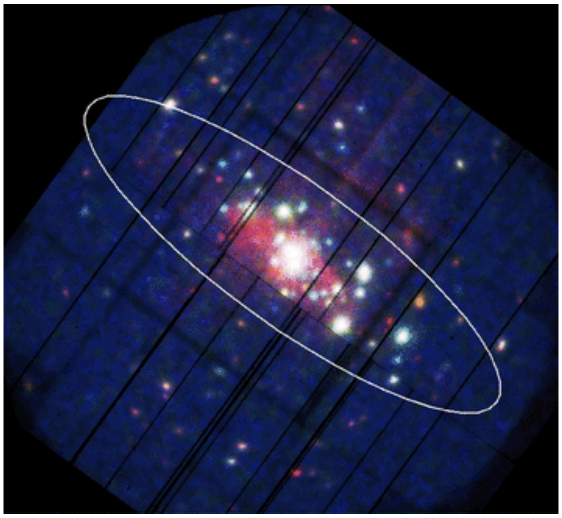

Figure 4. *XMM-Newton* image of NGC 253 (~4 Mpc). Image is 30′ on a side, with North up and East to the left. *HEX-P* will have similar spatial resolution, but will be more sensitive and probe much higher energies. This illustrates that *HEX-P* will be able to study high-energy populations in the local universe. From Barnard *et al.* (2008).

2.4. Compact Objects in the Local Group and Nearby Universe

HEX-P will extend hard X-ray studies of the local universe to fainter levels, enabling the detection of large numbers of compact objects (*e.g.,* black holes, neutron stars, and white dwarfs) in our Galaxy and nearby galaxies. In many cases, individual objects are of interest for understanding accretion processes in, *e.g.,* X-ray binaries and Cataclysmic Variables (CVs), or for studying extreme objects such as highly magnetic or rapidly rotating neutron stars (*e.g.,* magnetars and accreting millisecond pulsars, respectively). However, it is only by finding large numbers of these sources that we begin to obtain a full picture of how populations evolve from groups of single and binary, high-mass and low-mass stars to reach their compact object end states. 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. The increased sensitivity means that in the same exposure time, *HEX-P* reaches comparable depths for M82 or NGC 253 (~4 Mpc; Fig. 4) as *NuSTAR* reaches for M31 (~700 kpc). In addition, *HEX-P* will be able to measure the broad band spectrum across a very large range of accretion rates, down to quiescence. This will permit us to study how the emitting processes depend upon the accretion rate.

HEX-P will also provide unique and important information on star-forming galaxies in the local universe (*e.g.,* Fig. 4). Star-forming galaxies are the most numerous X-ray emitting extragalactic population, and there is a clear link between HMXBs and star formation (*e.g.,* Grimm *et al.* 2003; Mineo *et al.* 2011). However, we currently know very little about the hard X-ray emission properties of star-forming galaxies. *HEX-P* will probe the bulk hard X-ray properties of their binary populations, characterize the hard X-ray emission in individually detected ultraluminous X-ray (ULX) sources, and place constraints on diffuse Inverse Compton (IC) emission. ULXs are of particular interest, since hard X-ray measurements are essential for studying the accretion mechanisms, and are thus important for understanding if the most luminous ULXs indeed harbor intermediate-mass black holes. *Fermi* observations have revealed cosmic ray acceleration to be quite strong in starburst galaxies (Abdo *et al.* 2010); starburst galaxies may contribute quite strongly to the cosmic γ-ray background (*e.g.,* Fields *et al.* 2010). *HEX-P* will measure starburst galaxy contributions to the 10-40 keV background and inform starburst cosmic ray acceleration models (*e.g.*, Persic & Rephaeli 2003). In particular, X-ray binaries emit a significant fraction of their energy in harder X-rays. It is difficult to extrapolate observations at E<10 keV to higher energies due to the variability of X-ray binaries, uncertainty regarding the range of X-ray states and time binaries spend in those states, as well as the bias against objects with high absorbing column densities ($N_H > 10^{23}$ cm^{-2}). *HEX-P* will provide an unbiased survey of the hard X-ray populations in the Local Volume.

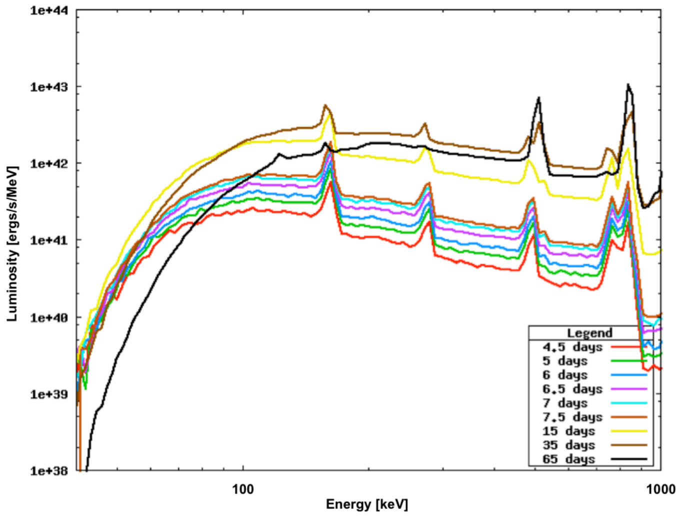

Figure 5. Simulated γ-ray spectrum at a number of days post-explosion (Fryer, Hungerford *et al.,* private communication). Lines of both ^{56}Ni (158, 749, 812 keV) and ^{56}Co (847, 511 keV) are prominent, as well as the Compton-scattered continuum. Shape and flux of this continuum agrees well with the previous spectra from Burrows & The (1990).

2.5. **Supernovae**

SNe Ia, the thermonuclear explosions of degenerate white dwarfs, are profoundly radioactive events. As much as 50% of the white dwarf mass is fused to ^{56}Ni (t_{half}= 6.1 d). After a short time, it is the decay of ^{56}Ni and its daughter, ^{56}Co (t_{half}= 77 d), which power the entire visible display of the supernova. Most of this power, however, is emitted in the form of γ-ray lines, some of which begin to escape after several days (Fig. 5). While these γ-ray lines are the most direct diagnostic of the dominant processes in the nuclear burning and explosion, they are inaccessible to current γ-ray instruments. *HEX-P* will be sensitive to the 158 keV line from ^{56}Ni as well as photo-absorbed Compton-scattered continuum from these lines which extends down into the *HEX-P* bandpass and will be detectable for SNe Ia within ~70 Mpc. The local supernova rate within this distance is ~40 per year. The flux and spectral shape of the γ-ray line and this hard X-ray component are sensitive to both the overall nucleosynthesis (flux of the line and Compton-scatter continuum) and the amount of mixing in the ejecta (measured by the width of the line and the photo-absorption).

Despite extensive study of SNe Ia, and their use in cosmology, major fundamental questions about these explosions remain unanswered. For example, we do not know their progenitor systems (Branch *et al.* 1995). Almost certainly they occur in binary systems, but the nature of the companions, whether normal stars, white dwarfs, or some of each, is unknown. Thermonuclear supernovae are also grand experiments in reactive hydrodynamical flows. We do not understand how the nuclear flame propagates, how it proceeds as fast as it does, or how and when it turns into a shock (or even if, though there is some evidence that it does) and propagates supersonically (Hillebrandt & Niemeyer 2000). We do not know to what extent instabilities break spherical symmetry, or whether their effects are wiped out by subsequent burning if they do. We do not fully understand the empirical correction to their magnitudes that allows them to be used as standard candles for measuring the geometry of our universe. Nuclear γ-ray lines from SNe Ia hold the key to solving these mysteries. *HEX-P* will provide significant gains through study of the ^{56}Ni γ-ray line and hard X-ray Compton-scatter component.

2.6. **Other Science Objectives**

In addition to the four primary science objectives listed above, *HEX-P* will be an extremely capable and flexible platform for a broad suite of additional science programs. We briefly list a few such programs below.

• *X-ray timing of Galactic black holes and neutron stars. RXTE* found that most types of quasi-periodic oscillations (QPOs) found in X-ray binaries show a strong increase in amplitude with energy (van der Klis 2006, and references therein). The high-frequency QPOs can be used to probe the inner regions of the accretion disk and the compact objects themselves, and the highest-frequency QPO that has been detected from a black hole binary was detected in the 13-27 keV bandpass but not at lower energies (Strohmayer 2001). Extending timing studies to higher energies with *HEX-P*, where the QPO signals may be even stronger, opens up new discovery space. This science directly addresses two of *IXO*'s primary science objectives: *What happens close to a black hole?* and *How does matter behave at very high density?*

• *Millisecond pulsars (MSPs). Fermi* has been a surprisingly powerful facility for finding radio pulsars, especially MSPs, showing that many should be detectable at high energies by *HEX-P*. Besides studying the physics of these sources from sensitive, high-energy observations, MSPs can also be used as precise clocks to measure gravitational waves. Scintillation by the interstellar medium ultimately limits the precision that can be obtained in the radio band, and observations at γ-ray energies are not feasible because of the long exposure times required simply to detect sources. X-rays would avoid these issues, but likely require the sensitive, high-energy capabilities of *HEX-P* since many MSPs are quite faint below 10 keV. Along similar lines, MSPs near the Galactic center might best be discovered with a focusing, hard X-ray mission. Radio waves are scattered, soft X-rays absorbed, and coded-mask facilities suffer from source confusion. Were *HEX-P* to find an MSP near Sgr A*, it would provide a unique laboratory to study the effects of relativistic gravity (*e.g.,* Pfahl & Loeb 2004).

• *Dark matter annihilation.* A large range of dark matter models predict detectable signals in the hard X-ray energy band due to inverse Compton scattering of microwave background photons by electrons and positrons produced by dark matter annihilation and decay events (*e.g.,* Jeltema & Profumo 2011). *HEX-P* observations of dark-matter-rich targets like galaxy clusters and the Galactic Center will significantly improve constraints on low- to intermediate-mass WIMP dark matter (< few hundred GeV) relative to *NuSTAR* and *Fermi,* and will precisely probe the particle mass range that will be inaccessible to next generation γ-ray facilities such as the Cherenkov Telescope Array (CTA).

3. Mission Concept

3.1. Mission Overview

HEX-P will launch into a circular low-Earth orbit with near-equatorial inclination. This orbit choice results from a detailed analysis of the overall sensitivity of the mission; detector background dominates sensitivity over a wide energy range and is minimized in a near equatorial orbit at altitudes <600 km, even accounting for observing efficiency. The mass and volume of *HEX-P* (see Table 2) exceeds the capability of Pegasus or Falcon 1e class vehicles but could easily be accommodated on a Falcon 9, which could inject *HEX-P* into the desired orbit from either the current Cape Canaveral launch site (with a dogleg insertion into ~3° inclination) or the proposed SpaceX Kwajalein facility.

The *HEX-P* spacecraft will be a 3-axis stabilized platform with a sun-pointing solar array actuated on one-axis. Reaction wheels with magnetic torque bars provide arcminute pointing with no expendables. Downlink will be via X-band to equatorial ground stations, which provide for flexible scheduling for the daily downlinks. The spacecraft requirements overall are relatively unchallenging; the only technical issue is the 20 m mast, which, at the *HEX-P* mass, provides approximately 400 milliNewton-meters of gravity gradient torque. This disturbance torque can be accommodated with standard reaction wheels but would require somewhat larger magnetic torque bars than is usual for this type of system; the mass of these bars is accounted for in the mission mass estimate.

3.2. Optics Overview

The optics modules for *HEX-P* are straightforward extensions of the *NuSTAR* modules. Glass substrates are thermally formed through a slumping process, coated with multilayer structures to enhance high-energy reflectivity, and mounted into a monolithic structure which is stable at the arcsecond level throughout launch and on-orbit operations.

There are two primary updates to the *NuSTAR* optics design. First, for *NuSTAR*, which has 50″ performance (half-power diameter) against a 60″ requirement, the budget and schedule did not allow for glass forming mandrels that matched the desired conical shape of the substrates. The deviation between the desired radius and, especially, the cylindrical versus conical mandrels, dominated the figure error budget. To meet the *HEX-P* sensitivity requirements the cylindrical mandrels, which were spaced at three layer increments, will be replaced with conical mandrels of the desired radius for all 390 layers. With this approach *HEX-P* takes full advantage of the better than 10″ substrate performance demonstrated by GSFC during the latter part of *NuSTAR* production and for *IXO* development. A direct linear scaling from the demonstrated performance, should readily achieve 15″ performance. The primary technological challenge is in the substrate mounting, which must be improved relative to *NuSTAR*.

Second, the preferred coatings for *HEX-P* are NiV/C. *NuSTAR* demonstrated a remarkable insensitivity to coating stress which varied by factors of three among the Pt/C and W/Si flight coatings used. Some coating development work is required to tune the new NiV/C material combination; however, the demonstrated versatility during *NuSTAR* production (where three separate material combinations were deposited with the d-spacing and rates required for *HEX-P*) provides confidence that the technology risk is low. Assembly of the coated substrates will use the flight-proven *NuSTAR* approach taking advantage of existing NASA-funded infrastructure with modest upgrades required to accommodate the extra *HEX-P* layers.

3.3. Focal Plane Overview

The *HEX-P* focal plane, similar to that proposed for *IXO's* WFI/HXI, is based on technologies developed for *NuSTAR* and *eROSITA*. A Silicon active pixel sensor, similar

Table 2. Key technical parameters.

Parameter	***NuSTAR***	***HEX-P***	**Notes**
focal length	10 m	20 m	30% increase in mast diam. provides similar performance
mass	380 kg	1061 kg	driven by optics and ACS
volume	1 m diameter × 1 m height	2.2 m diameter × 1.6 m height	driven by optics module
power	550 W BOL	900 W BOL	driven by thermal and ACS
orbit	575 × 600 km 5° inclination	650 × 650 km 2-7° inclination	altitude driven by lifetime vs. background trade
launch vehicle	Pegasus	Falcon 9	CCAS or Kwajelein launch
lifetime	2 yr.	5 yr.	no consumables
optics	2 modules 133 layers Pt/C + W/Si	3 modules 390 layers NiV/C + W/Si	
focal plane	CdZnTe	Si CCD + CdTe	similar readout to *NuSTAR*
metrology	2 laser units	3 laser units	tracks mast motion

to those used on *eROSITA,* will be placed in front of a CdTe detector hybrid based on Caltech's custom low-noise readout so that the full energy range can be covered with good spectral resolution. While *NuSTAR* utilized CdZnTe, *HEX-P* will replace the sensor with CdTe detectors with blocking contacts. These sensors have been developed by Acrorad, and performance when coupled to the Caltech ASIC is excellent (Miyasaka *et al.* 2009). Because of the longer focal length and consequent larger plate scale, no improvement in pixel size is required for the CdTe to achieve the 15″ angular resolution requirement. Improvements are necessary in the ASIC readout to reduce the deadtime by a factor of four, which is achievable with an updated processor architecture.

3.4. Rough Order-of-Magnitude (ROM) Cost Estimate

The cost estimate presented in this document does not constitute an implementation-cost commitment on the part of JPL or Caltech. The estimate was prepared without consideration of potential industry participation and was derived using a combination of parametric estimates and analogies to comparable historical mission actual costs. The accuracy of the cost estimate is commensurate with the level of understanding of a Pre-Phase A mission concept. The *HEX-P* Phases A-F cost estimate is $483M (FY12), which includes the launch vehicle and five years of science operations. All aspects of the mission have a technology readiness level (TRL) of 6 or higher. The cost estimate is provided in Table 3 and is based on the following methodology and assumptions:

Costs for HEX-P were derived directly from NuSTAR actuals.

- *Project Management (PM), Systems Engineering (PSE) and Safety and Mission Assurance (SMA)*. The cost is calculated as 13.5% (4% PM, 4.5% PSE, 5% SMA) of the payload, spacecraft, and ATLO cost. The percentage is based on comparable historical mission averages; *NuSTAR* is 11.3%.
- *Science.* The development portion of the cost (Phases A-D) is calculated as 2.7% of the payload, spacecraft, and ATLO cost, based on *NuSTAR* actuals. The operations cost (Phases E-F) is $6.6M per year for data analysis, based on *Spitzer* actual costs.
- *Payload*. The instrument cost is developed using the NICM subsystem model normalized to the *NuSTAR* actual costs and then scaled up for the *HEX-P* instrument mass. The estimate was then validated using PRICE-H calibrated to *NuSTAR* to ensure reasonableness.
- *Spacecraft.* The spacecraft cost was developed using the Small Satellite Cost Model (SSCM) normalized to the *NuSTAR* actual costs and then scaled for the partial redundancy and higher mass and power required for *HEX-P*. The estimate was then validated using PRICE-H calibrated to *NuSTAR* to ensure reasonableness.

Table 3. ROM cost estimate ($M, FY12).

WBS	Dev	Ops	Total	Notes
PM/PSE/SMA	23.4	8.6	32	historical mission average wrap rates
Science	4.7	33.0	37.7	Dev based on *NuSTAR*; Ops based on *Spitzer*
Payload	107.9		107.9	NICM + PRICE model
Spacecraft	65.2		65.2	SSCM + PRICE model; includes ATLO
MOS/GDS	7.8	90.0	97.9	Dev based on *NuSTAR*; Ops based on *Spitzer*
Launch vehicle	56.0		56.0	SpaceX published cost for Falcon 9
E/PO	2.1	1.3	3.4	1% of total, excluding Reserves and LV
Reserves	63.3	19.9	83.2	30% Phases A-D, excluding LV; 15% Ph. E-F
Total	**330.3**	**152.9**	**483.2**	

- *Mission Operations Systems/Ground Data Systems*. The development portion of the cost (Phases A-D) was calculated as 4.5% of the payload, spacecraft, and ATLO cost. The percentage is based on the *NuSTAR* actual costs. As *HEX-P* will be a guest observatory, similar in structure to *Spitzer*, the operations cost (Phases E-F) is based on the *Spitzer* actual cost of $18M/year.

- *Launch Vehicle (LV)*. The mass of *HEX-P* is within 100 kg of the Falcon 1e capability for a Kwajalein launch, which offers the possibility of a $40M cost savings if the mass-to-orbit for the Falcon 1e configuration is validated over the next two years.

3.5. **Areas for Research and Technology Development**

The instrument requires a moderate level of technology development. The most challenging aspect is improving the optics angular resolution from the 50″ HPD achieved for *NuSTAR* to 15″. While no improvement over that demonstrated is required for the substrate production, the mounting must be improved. Although the same basic approach will work, a number of modifications of the *NuSTAR* process must be made to ensure the figure of the mounted substrates is not distorted at the 8″ level (the mounting allocation to the error budget). In addition, prototypes must be built to demonstrate mounting at the larger *HEX-P* radii. The performance of the NiV/C coatings also requires demonstration, especially in a production setting.

The basic detector technologies have been demonstrated by the MPE (Si) and Caltech (CdTe) groups respectively. In order to achieve *HEX-P*'s timing goals, the Caltech ASIC must be modified to reduce readout deadtime and implement a fast-timing mode. This modification is straightforward, but should be undertaken early in the program. Studies must be performed to understand the complexity of the thermal design, and the required degree of active cooling. Development of a full hybrid prototype should also be carried out prior to mission start. This mission concept includes no controlled information, and we are willing and eager to present *HEX-P* at a NASA-sponsored workshop.

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