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The *Lynx* X-ray Observatory: Concept Study Overview and Status

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ABSTRACT

Lynx, one of four strategic mission concepts under study for the 2020 Astrophysics Decadal Survey, will provide leaps in capability over previous and planned X-ray missions, and will provide synergistic observations in the 2030s to a multitude of space- and ground-based observatories across all wavelengths. *Lynx* will have orders of magnitude improvement in sensitivity, on-axis sub-arcsecond imaging with arcsecond angular resolution over a large field of view, and high-resolution spectroscopy for point-like and extended sources. The *Lynx* architecture enables a broad range of unique and compelling science, to be carried out mainly through a General Observer Program. This Program is envisioned to include detecting the very first supermassive black holes, revealing the high-energy drivers of galaxy and structure formation, characterizing the mechanisms that govern stellar activity - including effects on planet habitability, and exploring the highest redshift galaxy clusters. An overview and status of the *Lynx* concept are summarized.

Keywords: *Lynx* X-ray Observatory, X-Ray Astronomy, Strategic Mission Concept, 2020 Astrophysics Decadal

1. INTRODUCTION

Two years ago, four large strategic mission concepts, based on those defined in the Astrophysics Roadmap - Enduring Quests, Daring Visions[1], were selected by the astronomy community to be studied for prioritization in the 2020 Astrophysics Decadal Survey. Of these missions, *Lynx*, formerly X-Ray Surveyor, is the only concept that would enable the next generation of high-energy observations of the Universe. Since being selected for study, the *Lynx* concept has evolved into a streamlined general-purpose observatory capable of performing science befitting that of a flagship mission for a cost that would allow for a balanced Astrophysics portfolio.

1.1 Fascinating Observations

Rooted in the X-ray band, *Lynx* will operate in the 0.2 keV to ~10 keV energy range and boasts a 50-fold increase in sensitivity compared to the currently orbiting *Chandra* X-Ray Observatory, and 100-fold increase in sensitivity compared to ESA's planned *Athena*. These gains are possible by coupling high-angular resolution with high throughput. *Lynx* will also have 16 times larger field of view (FOV) for sub-arcsecond imaging and 10–20 times higher spectral resolution for both point-like and extended sources. This performance is made possible by several key technologies that have significantly matured over the past decade and includes relatively thin, lightweight X-ray mirrors, large-scale active pixel sensors, X-ray microcalorimeters, and high-resolution gratings. These technologies that have a clear path for maturation within a decadal-driven timescale, lowering risk and ultimately the cost of such an ambitious mission.

The *Lynx* architecture is motivated by a dynamic science case to observe the first supermassive black holes and to understand the critical drivers of galaxy and stellar formation and evolution; phenomena only evident at high-energies. *Lynx* couples a large area, high-resolution, mirror assembly with good wide-field performance (0.5 arcsecond Half Power Diameter (HPD) on-axis, <~1 arcsecond to ~10 arcminutes) to a suite of three science instruments that includes

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the High Definition X-ray Imager (HDXI)[2,3,4], the *Lynx* X-ray Microcalorimeter (LXM)[5], and the X-ray Grating Spectrometer (XGS)[6,7]. Multiple candidate technologies for the *Lynx* mirrors exist, three of which are being studied in detail by the *Lynx* Team. These optics technologies are Full-Shell Optics developed by Brera and Marshall Spaceflight Center (MSFC)[8,9], Silicon Meta-shell Optics developed by Goddard Spaceflight Center (GSFC)[10], and Adjustable Segmented Optics developed by the Smithsonian Astrophysical Observatory (SAO)[11].

1.2 Designing an Observatory

The spacecraft and mission design leverage existing heritage and benefit from simplicity of operation. *Chandra*, for example, has produced many Lessons Learned[12] that *Lynx* will incorporate. The spacecraft design and mission operations borrow heavily from the *Chandra* Observatory, the only X-ray observatory to date to achieve sub-arcsecond angular resolution[13]. *Lynx* maneuvers and operational procedures on-orbit are close to identical to *Chandra's*, and similar design approaches target longevity. *Chandra* has been operating for nearly 20 years, and has maintained a robust science program throughout[14]. *Lynx* will have a baseline mission lifetime of 5 years, extendable to 20 years without servicing (though accommodation will be made to facilitate servicing as mandated by Congress[15]).

Lynx is a much more ambitious observatory (e.g., larger effective area and more advanced science instruments) than *Chandra*, and will operate in a different environment (halo orbit around Sun-Earth L2 versus highly elliptical orbit around the Earth). As such, *Lynx* will take advantage of many recent advances in the current state-of-the-art in the focal plane design, propulsion systems, power system, avionics, and command and data handling. A Cooperative agreement Notice (CAN) was awarded to a team at Northrup Grumman Aerospace Systems (NGAS), Ball Aerospace, and Harris Corporation to assess the design approach as it relates to the use of heritage[16].

1.3 State of Readiness

A preliminary Program schedule for the *Lynx* has Phase A starting in 2024, leading to a launch in the mid- 2030s. Each of the *Lynx* technologies has a clear development and maturation path for reaching a Technology Readiness Level of 6 by the Project Preliminary Design Review in 2028 and for meeting Critical Design Review in 2030. All of the *Lynx* enabling technologies are currently at a TRL of 3 or higher, and it is expected that all will be at or approaching a TRL 4 by mid- 2020. Each of these technologies is being funded through NASA competed opportunities or directed funding, internal institutional funding, and other pre-flight Programs.

Manufacturing the hundreds to thousands of *Lynx* X-ray Mirrors is on the critical path and steps must be taken to balance the cost, schedule and risk for this effort. A CAN was awarded to NGAS and Harris to perform a cost, schedule, and risk assessment of the manufacturing aspects of the various mirror designs considered by the *Lynx* concept study[17].

2. LYNX X-RAY TELESCOPE

The *Lynx* telescope design flows directly from the science requirements established by the Science and Technology Definition Team supported by a large number of Science Working Group members. Since reporting on the status of the *Lynx* concept in 2017[18], the *Lynx* pillars, which are used to define the observatory architecture and define the mission requirements, now includes a broad topic regarding stellar evolution and ecosystems. The three science pillars, to be primarily carried out under a General Observer (GO) program, include:

The Dawn of Black Holes: Massive black holes start to form as early as their host galaxies. *Lynx* will find the first supermassive black holes in the first galaxies detected by *JWST*, trace their growth from the seed phase, and shed light on how they subsequently co-evolve with the host galaxies. Reaching into the seed regime in the early Universe requires X-ray sensitivities of $\sim 10^{-19}$ erg s^{-1} cm^{-2}. These observations require *Lynx* to have a large effective area (around 2 m^2 at 1 keV) and large FOV with sub-arcsecond or better angular resolution.

The Invisible Drivers of Galaxy Formation and Evolution: The assembly, growth, and state of visible matter in cosmic structures are largely driven by violent processes that produce and disperse large amounts of energy and metals into the surrounding medium. In galaxies at least as massive as the Milky Way, the relevant baryonic component is heated and ionized to X-ray temperatures. Only *Lynx* will be capable of mapping this hot gas around galaxies and in the Cosmic Web, as well as characterizing in detail all significant modes of energy feedback. Essential observations require high-resolution spectroscopy ($R \sim 5{,}000$) of background active galactic nuclei (AGNs), the ability to detect low surface brightness continuum emission, and $R \sim 2{,}000$ spectroscopy of extended sources on arcsecond scales—unique to *Lynx*.

The Energetic Side of Stellar Evolution and Stellar Ecosystems: *Lynx* will probe, with unprecedented depth, a wide range of high-energy processes that provide a unique perspective on stellar birth and death, internal stellar structure, star-planet interactions, the origin of elements, and violent cosmic events. *Lynx* will detect X-ray emission as markers of young stars in active star forming regions, study stellar coronae in detail, and provide essential insight into the impact of stellar X-ray and extreme ultraviolet flux and winds on the habitability of their planets. Images and spectra of supernova remnants in Local Group galaxies will extend studies of stellar explosions and their aftermath to different metallicity environments. *Lynx* will expand our knowledge of collapsed stars through sensitive studies of X-ray binaries in galaxies as distant as 10 Mpc and through detailed follow-ups of gravitational wave events. *Lynx* will greatly extend our X-ray grasp throughout the Milky Way and nearby galaxies by combining, for the first time, the required sensitivity, spectral resolution, and sharp vision to see in crowded fields.

The overall *Lynx* telescope design has not radically changed since previous reporting[18]; however, significantly higher fidelity has been designed into the observatory (**Figure 1**) and science instruments. The increased science instrument definition is a direct result of multiple instrument design studies involving the *Lynx* Instrument Working Group and the instrument design labs at both NASA MSFC and GSFC. The *Lynx* Mirror Assembly (LMA) includes the X-ray Mirror Assembly (XMA), retractable grating arrays, and the aft contamination cover. The contamination cover is used mainly on the ground to minimize contamination on the mirrors and gratings. Two of the science instruments, HDXI and the LXM, along with their electronics and radiators are mounted on a translation table that is part of Integrated Science Instrument Module (ISIM). Either instrument can be placed on-axis depending on the scientific objectives of a particular observation. A focus mechanism on the translation table allows for fine focus adjustment. The XGS focal plane detector assembly is mounted in a fixed location on the ISIM offset from the optical axis to intercept the dispersed spectrum regardless of whether the HDXI or LXM is at the primary focus. The XGS focal plane assembly utilizes a separate focus mechanism that is integrated into its detector assembly.

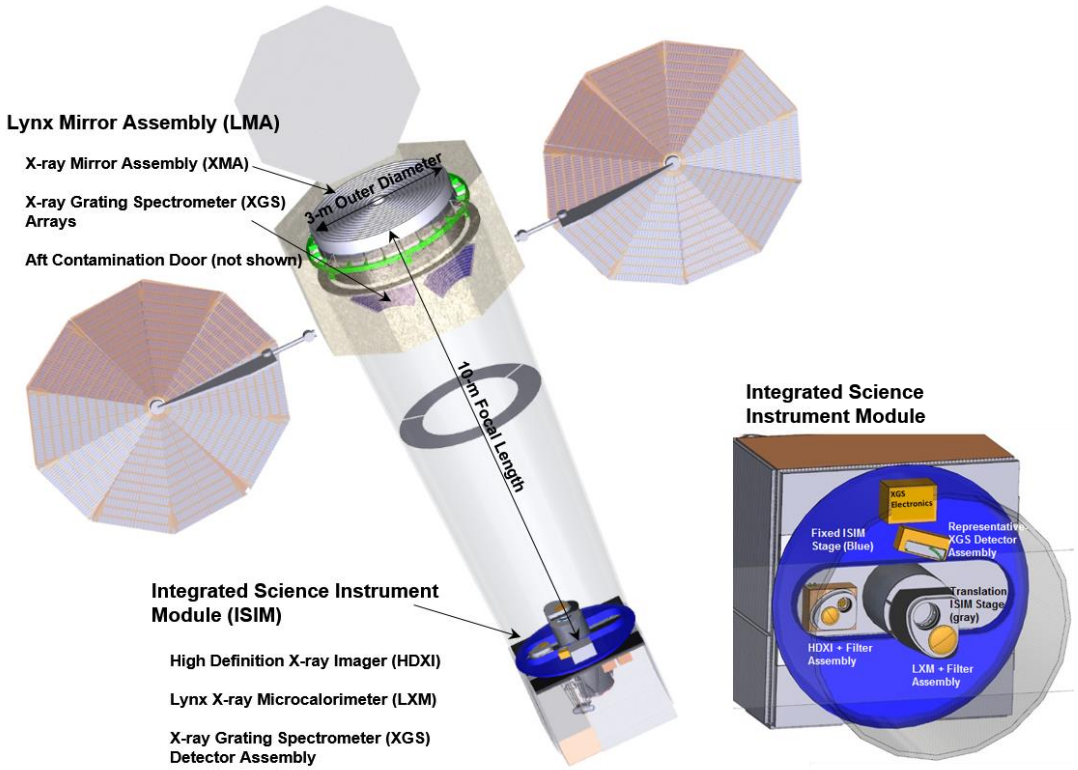


Figure 1. *Lynx* X-ray Telescope configuration. *Lynx* has a 10-m focal length and consists of a high-resolution, 3-meter diameter, large area X-ray mirror assembly with pre- and post-collimators (XMA) surrounded by the spacecraft bus and complemented by an instrument suite that includes HDXI, LXM, and XGS.

2.1 X-Ray Mirror Assembly

The most stringent requirement on the XMA is set by the *Lynx* science goal to observe the very first Supermassive Black Holes and associating them unambiguously with the first galaxies that *JWST* will observe[19].

On-axis angular resolution ~ 0.5 arcsecond (HPD) is required to avoid source confusion at the faintest fluxes and to uniquely associate X-ray sources with high-redshift optical and near-IR galaxies. A mirror effective area of 2 m^2 at 1 keV and a FOV with arcsecond or better imaging extending to at least 10 arcminutes off-axis is required to adequately sample the population of black hole seeds at high redshift well within the mission lifetime. *Lynx* will enable a 100-fold increase in survey depth over the deepest *Chandra* fields, whereas *Athena* will be confusion- and background-limited before even reaching the current *Chandra* deep field sensitivity (**Figure 2**).

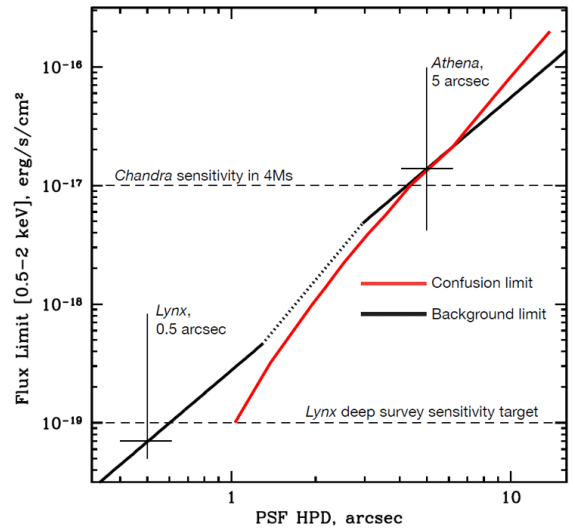


Figure 2. Sensitivity vs. angular resolution is shown, indicating that *Lynx* will not be confusion limited at the required sensitivity for deep surveys of the first SMBHs.

2.2 Science Instruments

Just as critical as the mirror assembly, *Lynx* requires a detector capable of direct imaging black hole seeds in deep extragalactic fields, taking full advantage of the mirror assembly angular resolution and FOV. In addition, this detector must have excellent soft X-ray spectral response to these (redshifted) sources and have moderate spectral resolution across the ~0.2 to ~10 keV band to deduce thermodynamic properties of the hot gas in galactic halos and other extended objects. A silicon active pixel sensor array of fine pixel scale (0.3 arcsecond) and large format (23 arcminutes x 23 arcminutes FOV), such as HDXI, is capable of meeting these requirements[2].

Lynx also requires a non-dispersive imaging spectrometer that can spatially resolve Active Galactic Nucleus (AGN) feedback signatures from surrounding hot gas and jets in galaxies, groups, and clusters on 1 arcsecond or finer scales. This detector must resolve starburst-driven winds in low-redshift galaxies at high spectral resolution (~0.3 eV) over ~1 arcminute FOVs at 1 arcsecond imaging resolution; map metallicity gradients (better than 5 eV resolution over 5 arcminute FOV) in circumgalactic, group, and galaxy cluster fields; and survey young Supernova Remnants (SNRs) in Local Group galaxies. This will be accomplished with a *Lynx*-unique microcalorimeter, such as LXM, which is designed to have multiple sensor arrays that meet these combinations of spectral, spatial, and FOV requirements (**Figure 3**)[5].

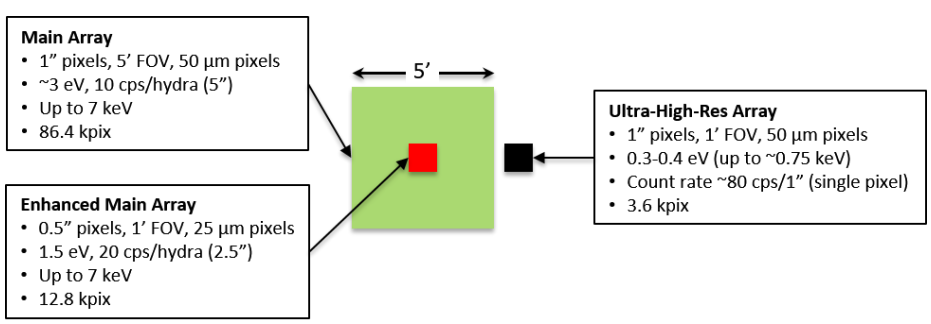


Figure 3. Baseline layout of the LXM array. There are three different regions of the array corresponding to three different pixel types, each with different properties as labeled.

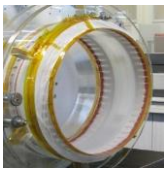
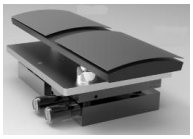
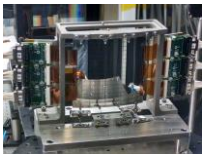
Lynx must also have an instrument capable of characterizing warm gas in galactic halos out to their virial radius. This can be accomplished by absorption line studies of background AGNs requiring a high-spectral resolution (R=5,000) dispersive grating spectrometer such as XGS[6], sensitive in the 0.2-2.0 keV band, capable of 1 mÅ sensitivity in key absorption lines of OVII and OVIII.

2.3 Trade Studies

The *Lynx* mission concept was formulated, and is being refined as a result of multiple trade studies on the telescope configuration (e.g., XMA diameter and focal length for different configurations and fixed versus extendable bench), telescope technologies (e.g., X-ray mirror technologies and detector filters), and mission design parameters (e.g., launch vehicle, orbit). Of these, one of the most critical is the trade study on the X-ray optics technology.

Multiple, actively funded, X-ray mirror technologies will be able to meet the *Lynx* science requirements. Deciding which of these technologies should be used for integration into the Design Reference Mission (DRM) requires careful scrutiny, as each technology has unique advantages and challenges, and each has a different development path for maturation. These technologies include Full-Shell Optics, Silicon Meta-shell Optics, and Adjustable Segmented Optics. Challenges common to all three technologies and state-of-the-art TRL are given in **Table 1**. Selection of a mirror technology for the DRM does not indicate which technology should be used for flight. That decision would only be made after selection of the *Lynx* mission, at which point each of these technologies, and perhaps others, would be assessed.

Table 1. X-ray Technologies considered for the *Lynx* DRM concept include Full-Shell Optics, Silicon Meta-Shell Optics, and Adjustable Segmented Optics. These three technologies are all expected to meet TRL 3 or TRL 4 by mid-2020. TRL Milestones were generated by the trade study team, and are used to evaluate, in a consistent way, the technologies relative to one another. The TRL 4 milestone is shown.

Technology	*Lynx* Requirements	Challenges (examples)	TRL
High-resolution, large-area, lightweight X-ray grazing incidence mirror assembly **Full Shell**  **Silicon Meta-Shell**  **Adjustable** 	• 2 m^2 Effective Area at 1 keV • 0.5 arcsecond on-axis, on-orbit system angular resolution • Minimum grasp of 600 m^2 $arcmin^2$ at < 1 arcsecond resolution, at 1 keV • 3 m maximum outer diameter for the XMA to maintain flexibility in launch vehicle selection without compromising science	• Low areal cost and mass • Maintain high precision figure through coating, post-fabrication figure correction, alignment, and mounting • Maintain performance on-orbit	• All technologies are at TRL > 2 and are approaching a TRL3 to TRL 4 • NASA Definition TRL 4: A low fidelity system or component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment

<u>TRL 4 Milestone:</u> Must demonstrate a credible technology development path to the required on-orbit performance of the *Lynx* Mirror Assembly. Demonstrations must be traceable to the on-orbit performance requirement in the operational environment.

A credible demonstration of these Wolter-Schwarzschild optics must comprise the following:
- <u>Realistic end-to-end error budget</u> for *Lynx* Telescope angular resolution.
- <u>Laboratory demonstration</u> of measured angular resolution of mirror elements performing less than a factor of 3 away from their required performance (as stated in the error budget), executed under the following conditions:
  - An X-ray test of a single coated, co-aligned p-s mirror pair or a mounted single, coated full shell using a breadboard lab mount must be demonstrated. Mirrors must have nominal thickness consistent with their point design.
  - Functional breadboard mounting and all essential hardware elements (such as fixture to hold and transport full shell elements) demonstrated.
  - Full shell demonstration of the alignment of a single primary shell, aligned to optical axis as defined by the mount.
- <u>Models, Analogies, or Lab Demonstrations</u>
  - All elements related to the as-corrected mirror error contributions (e.g. coatings, thermal, g-release, etc.) must be validated.

The *Lynx* Team opted to use the Kepner-Tregoe[20] decision-making strategy for this trade study. This strategy uses a systematic approach to reaching group consensus on key differentiating criteria to satisfy a decision statement formulated by the stakeholders. The stakeholders for this study are the members of the *Lynx* STDT, and the decision

statement, or goal, is for the trade study team to recommend one DRM concept mirror architecture to focus the design for the *Lynx* final report and to identify all feasible alternates.

Trade study criteria includes Science, Technical, and Programmatic requirements. Each of these is broken down into two categories: absolute 'Musts' and relative 'Wants'. The 'Musts', of which there are 8 criteria (**Table 2**), are required to be met and are pass/fail. The 'Wants', of which there are 18 criteria (not shown here), have relative weightings and offer a comparative assessment between the technologies. Risks and opportunities are identified during this process and are an integral part of the evaluation.

Table 2. *Lynx* mirror technology trade criteria Kepner-Tregoe 'Musts'. The 18 'Wants' are not shown.

Science	Optical performance meets the requirements flowing down from Science Traceability Matrix
Technical	Credible roadmap from today's status to predict flight on-orbit performance
	Performance modeling tools related to current results are demonstrated to be credible
	Repeatable fabrication process based on current status
	Credible error budget that flows down to each mirror element
	Expected to survive launch
Programmatic	Credible plan to meet TRL 4-6
	Produce the mirror assembly within the Program schedule allocation

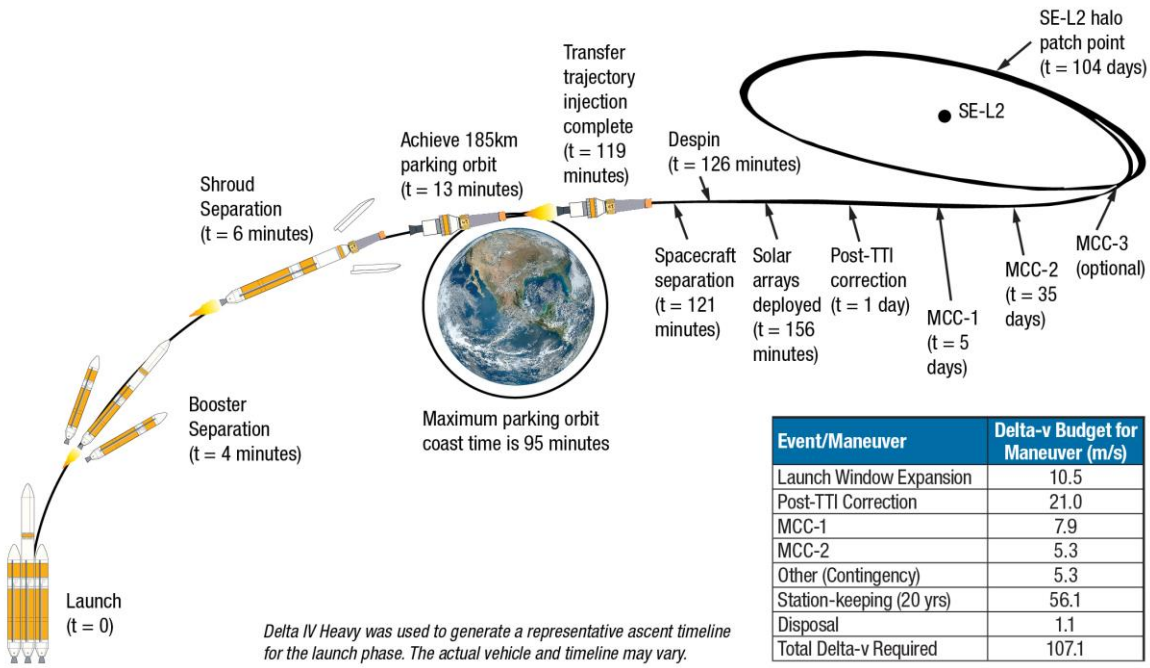
Each of the Kepner-Tregoe criteria is evaluated by a large team of experts chartered by the *Lynx* STDT. The recommended option, upon review by STDT and acceptance by the STDT Chairs, will serve as the reference design for the *Lynx* mission concept. All other feasible architectures identified in the trade process will be included in the *Lynx* final report. The evaluation team is a mixture of individuals both external and internal to the *Lynx* Program. They are volunteers from industry, the *Lynx* Science and Technology Definition Team, Universities, and other NASA Centers. Many of these individuals were heavily involved in the formulation and construction of *Chandra*, and have or are currently working on large flight Programs. The process is facilitated by G. Blackwood at NASA JPL, who has no affiliation with the technologies under consideration. A recommendation to the *Lynx* STDT is planned for early August of 2018.

3. LYNX MISSION

3.1 A Journey to SE-L2

Based on a preliminary Program schedule, *Lynx* is planning to launch in the mid-2030s and the current assumption (still under evaluation) is that *Lynx* will be integrated onto a Heavy class (expendable or recoverable) vehicle that will launch from NASA Kennedy Space Center. Following a transfer trajectory insertion (TTI) maneuver, *Lynx* will be inserted into the 800,000-km semi-major axis halo orbit around the SE-L2 libration point and operate for 5 years with consumables for 20 years. The launch to orbit timeline and delta-v budget is shown in **Figure 4.**

Several orbits were analyzed for *Lynx*, including SE-L2, Drift-away, Lunar Distant Retrograde Orbit (LDRO), *Chandra*-type Orbit (CTO), and Transiting Exoplanet Survey Satellite (*TESS*)-like. After careful consideration, SE-L2 was selected because it provides: 1) essentially no eclipsing, 2) a stable thermal environment, 3) avoidance of trapped radiation belts, 4) fewer maneuvers for orbit insertion and thus, relatively smaller propulsion system, and 5) a high observing efficiency of better than 85%. The observing efficiency is the percentage of actual time *Lynx* will spend on science observations and takes into account-estimated times for slewing, thermal and vibrational stabilization, and calibration.



Event/Maneuver	Delta-v Budget for Maneuver (m/s)
Launch Window Expansion	10.5
Post-TTI Correction	21.0
MCC-1	7.9
MCC-2	5.3
Other (Contingency)	5.3
Station-keeping (20 yrs)	56.1
Disposal	1.1
Total Delta-v Required	107.1

Figure 4. Launch to orbit timeline and delta-v budget.

3.2 Spacecraft Design and Operations

This timeline assumes launch on a Delta IV Heavy vehicle. Even though the Delta IV Heavy is not expected to be available in the 2030s, it is assumed to be representative of expected capability (and not necessarily cost) of the generic Heavy class vehicles in the 2030s. The *Lynx* concept team is also working with the SLS Program at MSFC to determine configuration options for launching *Lynx* on the SLS vehicle as a co-manifested payload. This option would provide considerable launch vehicle cost savings for the *Lynx* mission as launch vehicle costs are limited to integration services only. The current *Lynx* configuration easily meets the 10,000-kg and 7.2-m-diameter co-manifested payload envelope, but not the 8.4-m length limitation. To enable this option, the *Lynx* team is performing a trade study to determine the cost and risk associated with utilizing an extendable optical bench such that the observatory will fit within the SLS co-manifested payload envelope (as well as within an Intermediate-class launch vehicle envelope, mass allowing).

3.3 Science Operations

Following on-orbit activation and checkout, *Lynx* will operate primarily in Normal Mode, conducting an autonomous pre-planned science program. A typical scientific observing timeline includes a series of maneuvers between targets, target acquisition, and data collection. In this mode, the focal plane science instruments are either in a data collection or standby configuration, and the observatory attitude is maintained by the PCAD system under control of the onboard computer**.** Normal spacecraft operations such as switching focal plane instruments, instrument calibrations, momentum unloading, ground contacts, and recorder data playback all take place in Normal Mode.

All Normal Mode operations are preplanned using a scheduling process that seeks to maximize the time on-target while accommodating all necessary spacecraft operations. The mission schedule plan will be used to generate spacecraft and instrument commands, which are then uplinked to the spacecraft and stored. A sufficient number of commands will be loaded to assure autonomous operation for 72 hours. Stored command loads can be interrupted and updated as needed to accommodate Target of Opportunity (ToO) requests (and emergencies). It is anticipated that ToO requests may require up to 24 hours to initiate and review new command sequences, depending on spacecraft (thermal, power, momentum, and pointing) constraints, minimization of maneuver error, and the frequency of ground contact.

On-orbit calibration observations are performed as part of the Normal Mode science operations. A set of standard celestial targets will be determined for calibration use. These targets will be periodically observed to monitor LMA,

science instrument, and aspect system performance. In addition, HDXI and LXM contain in-situ calibration sources that are mounted on their filter assemblies. These will allow calibration data acquisition when those instruments are not carrying out celestial observations. As with other X-ray observatories such as *Chandra*, time allocations for calibration is expected to be about 5% of available observing time early in the mission and to decrease to 2–3% subsequently.

4. INTEGRATED APPROACH

An integrated analysis of the *Lynx* architecture has been initiated via an industry CAN partnership that involves NGAS, Ball Aerospace, and Harris Corp. participation. This study enables refinements to the current design, by considering the integrated observatory system, and producing an error budget for the on-orbit payload performance. Integrated studies include assessing the alignment of the *Lynx* XMA to the focal plane, alignment of the grating arrays to the focal plane, potential thermal and mechanical instabilities on the optical bench and impact on interface design, thermal gradients on the XMA, aspect system design and accommodation, and exported disturbances based on dynamic models on-orbit. This error budget will be used to update the observatory design, until all payload performance requirements are met. During this process, trades will be identified to optimize performance, cost, and schedule for the fully integrated system[16].

5. SUMMARY

The *Lynx* architecture was chosen to meet a demanding, yet realizable, science case to observe the first supermassive black holes in the Universe, trace the state of matter in cosmic structures, and to characterize the formation and evolution of stars and their local environments, including their planetary systems. The *Lynx* design is streamlined, employing relatively mature technologies for a concept phase and baselines standard spacecraft elements and heavy-class launch vehicles. The approach to design is integrative and system oriented, and focused on achieving the required on-orbit performance. Further, this approach will apply the appropriate lessons learned from previous missions to lower risk. The *Lynx* concept (artist conceptual drawing **Figure 5**) will be capable of flagship science for a cost that is compatible with a balanced Astrophysics portfolio.

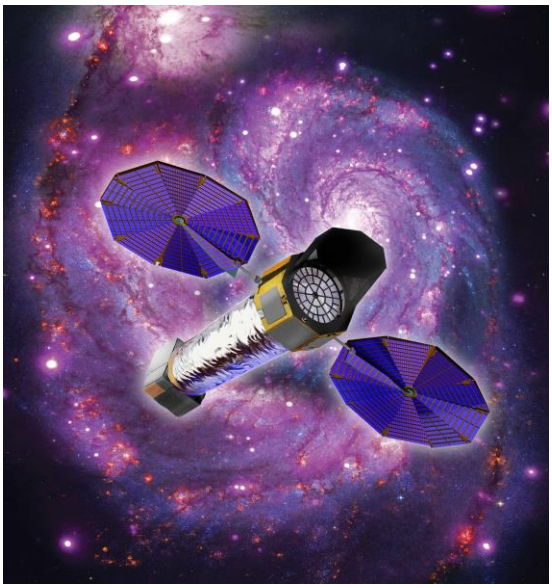


Figure 5. Conceptual design for *Lynx* based on the current designed architecture [Credit: David O. Miller].

6. ACKNOWLEDGEMENTS

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