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STROBE-X: Capturing the Universe in Motion

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ABSTRACT

The Spectroscopic Time-Resolving Observatory for Broadband X-rays (STROBE-X) is a proposed NASA Astrophysics Probe-class mission. STROBE-X is a time domain and multi-messenger mission designed to provide an unparalleled laboratory for probing strong gravity and the behavior of matter in extreme environments. The instrument suite encompasses a wide-field monitor and two pointed instruments to provide transient discovery and the capability for rapid follow-up with broadband (0.2–30 keV), high time resolution spectroscopy. Over 10,000 pointed observations will be conducted each year and STROBE-X will be able to slew to targets within minutes in response to transients triggered by on-board or ground alerts. Here, we present an overview of the STROBE-X science drivers, mission design, and instrument complement.

Keywords: X-ray, spectroscopy, time domain

1. INTRODUCTION

The field of transient astrophysics is experiencing a renaissance, with the arrival of multiple survey facilities spanning the electromagnetic spectrum and the computing tools necessary to grasp and analyze their data-intensive products. The past decade has also seen the advent of multi-messenger (MM) astrophysics, adding gravitational waves and high-energy neutrinos to the time-domain arsenal. Transients energize their host galaxies, produce and inject heavy elements into the universe (playing a critical role in future star and planet formation), and include exotic compact objects — neutron stars and black holes — that are the source of many high-energy astrophysical phenomena. Transients enable astronomers to probe the behavior of matter in extreme conditions: e.g., black hole spin across the mass spectrum, neutron star structure, magnetic field geometries, neutrino production, matter in the strong gravity regime, and general relativity. Their broad impact is why the study of transients involves most sub-fields of astronomy and many physics disciplines. They also lie at the heart of the new age of time-domain and multi-messenger astrophysics (TDAMM).

To advance the broad science impacted by astrophysical transient observations, we must understand their underlying engines, with key measurements residing in the X-ray band. The quantity of high energy data on transients has grown immensely, with a huge archive from multiple missions (i.e. Swift, Fermi, RXTE, and NICER). However, these missions lacked one or more critical capabilities: a large field-of-view (FoV), large effective area ($A_{\rm eff}$), broadband spectral coverage, and/or high time resolution. Because transients occur randomly across the sky, a large FoV is required to rapidly identify and localize them for detailed follow-up. Transients also span a large dynamic range in flux, timescale, and X-ray bandpass, requiring instrumentation that accommodates wide ranges in all three with sufficient sensitivity on all variability timescales.

The Spectroscopic Time-Resolving Observatory for Broadband Energy X-rays (STROBE-X) will obtain exactly these observations (Fig. 1). STROBE-X is a proposed mission that conducts broad energy band spectroscopy of time-variable targets and discovery of new sources. It continuously monitors the dynamic X-ray sky to detect and localize new transients and follows up with broadband spectroscopy within minutes of an alert.

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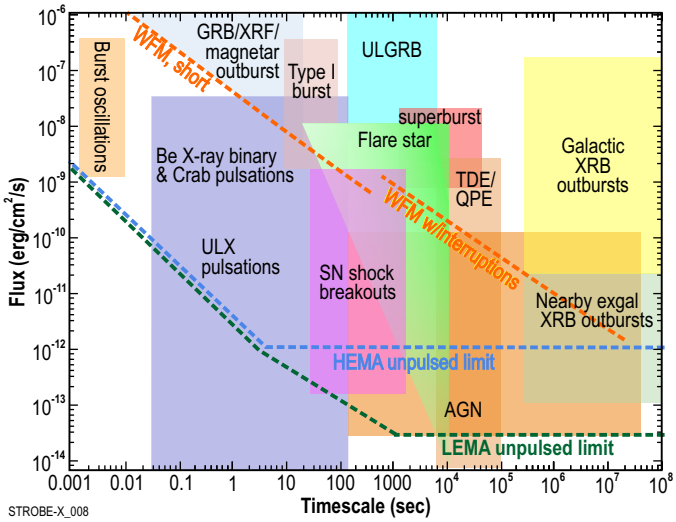

Figure 1. STROBE-X provides the X-ray eyes on the dynamic universe, observing transient sources and phenomena spanning 8 orders of magnitude in flux and 12 orders of magnitude in timescale.[1]

STROBE-X probes an enormous dynamic range in both timescales (from μs to years, with dense sampling, not just occasional visits) and fluxes (from faint pulsars to the brightest sources in the X-ray sky), making it extremely versatile and capable. With its huge collecting area, fast timing, good energy resolution, and broadband coverage, STROBE-X moves from discrete time-averaged snapshots that smear out any time evolution of targets to dynamic spectroscopy: broadband spectral "movies" that reveal the real-time evolution of astrophysical phenomena.

STROBE-X science observations will consist of a Guaranteed Time Observing program centered around the themes of Multi-Messenger Astrophysics, Explosive Transients, Gravity and Extreme Physics, and The Dynamic Universe. Over 72% of the observing time will go to the General Observer program, where the powerful instrument capabilities can be used to support a range of investigations of transient and variable sources at unprecedented sensitivity and time resolution.

STROBE-X has been proposed to the 2023 NASA Astrophysics Probe mission call. It answers two of the highest priority sustaining activities in space recommended in the 2020 Decadal Survey on Astronomy and Astrophysics (Astro2020):[2] fulfilling the call for a next-generation X-ray mission and expanding space-based time-domain and follow-up facilities in one powerful facility. STROBE-X is the subject of a special section in the Journal of Astronomical Telescopes, Instruments, and Systems (JATIS), in which the mission design, instruments, operational modes, and data products are presented in detail. Here, we present a mission overview and refer interested readers to the relevant special issue papers where appropriate.

2. MISSION OVERVIEW

The STROBE-X mission comprises the spacecraft, instrument suite, and operations support centers. The mission overview and spacecraft design is presented in detail in Ref. 1.

The redundant class C spacecraft is designed by Lockheed Martin using many of the spacecraft bus subsystems and architectures proven on previous missions such as VERITAS and DaVinci and modifying them for the unique needs of STROBE-X.[3,4] The observatory operates in a circular low-inclination orbit ($< 15°$ inclination) at altitudes from 550 to 575 km. Attitude knowledge is better than 20 arcsec with control better than 60 arcsec. The attitude control systems allow the spacecraft to slew 45° in 7.6 min and 90° in 11.5 min. This allows the pointed instruments to observe at least 3 targets per orbit and avoid observing inefficiencies caused by Earth occultations. A GPS receiver provides position, velocity and time knowledge to better than 100 ns. The spacecraft can point anywhere in the sky outside of a 45° exclusion zone around the Sun.

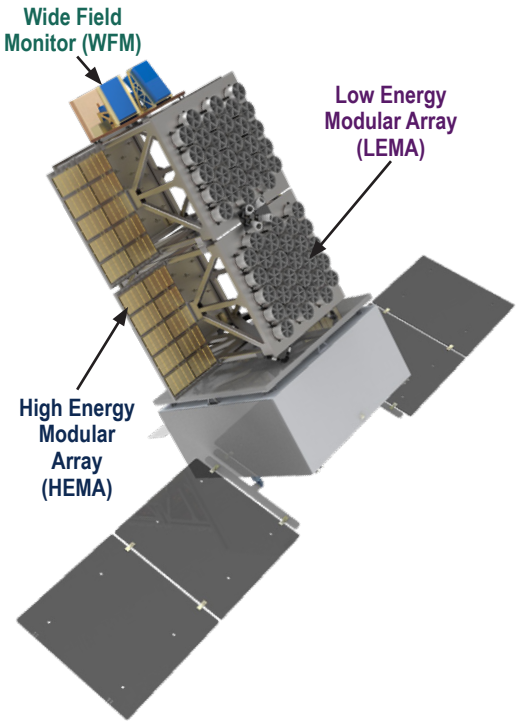

Figure 2. Rendering of the STROBE-X observatory, showing the 3 instruments.

The STROBE-X instrument suite comprises three instruments (Fig. 2): a wide-field monitor (WFM) that continuously scans the sky and two pointed instruments, LEMA and HEMA, that provide 0.2–30 keV broadband spectroscopy. When a transient trigger occurs, either via on-board detection with the WFM or from a ground alert, the rapidly slewing spacecraft autonomously points to the target in as little as nine minutes for an onboard trigger or fourteen minutes for an automated ground alert. Human-triggered targets of opportunity (ToO) can be processed by the mission operations center and executed within < 24 hours. Primary telecommunications are performed using commercial networks for uplink commands an downlink telemetry and data. With the decommissioning of TDRSS, a new capability for rapid dissemination of broadcast alerts and ToO uplinks with minimal latency is required. NASA is still defining the replacement for TDRSS, so the STROBE-X baseline design incorporates commercial space-to-space links to relay burst alerts to the ground within < 5 minutes and enable uplink of automated ground alerts from other facilities or multi-messenger triggers to be sent up to the spacecraft.

3. INSTRUMENTS

The STROBE-X instrument suite comprises the Wide-Field Monitor (WFM), the Low Energy Modular Array (LEMA) and the High Energy Modular Array (HEMA). The instruments rely on high-heritage technologies and instrument designs. LEMA is a scaled-up version of the NICER X-ray Timing Instrument currently operating on the International Space Station,[5] providing 8.5× more $A_{\rm eff}$ than NICER. HEMA and WFM have been developed for over a decade for the LOFT and eXTP concepts. HEMA provides 5.5× more $A_{\rm eff}$ than RXTE/PCA and both instruments have $\sim 3\times$ better energy resolution than that instrument.[6,7] Figure 3 shows the pointed instrument effective area performance compared to previous capabilities. The instrument designs are highly modular, which reduces cost and schedule risk during fabrication by enabling efficient integration flow and schedule flexibility.

LEMA is a 0.2–12 keV spectrograph with a 4 arcmin FoV (FWHM) and an energy resolution of 85 eV (at 1 keV). It consists of a 60 element array of concentrating optics feeding commercial silicon drift detectors (SDDs). LEMA is a very high heritage instrument, as it is directly based on the NICER instrument, scaled up to a larger area and longer focal length. Reference 8 presents the LEMA design in detail. LEMA also acts as the optical

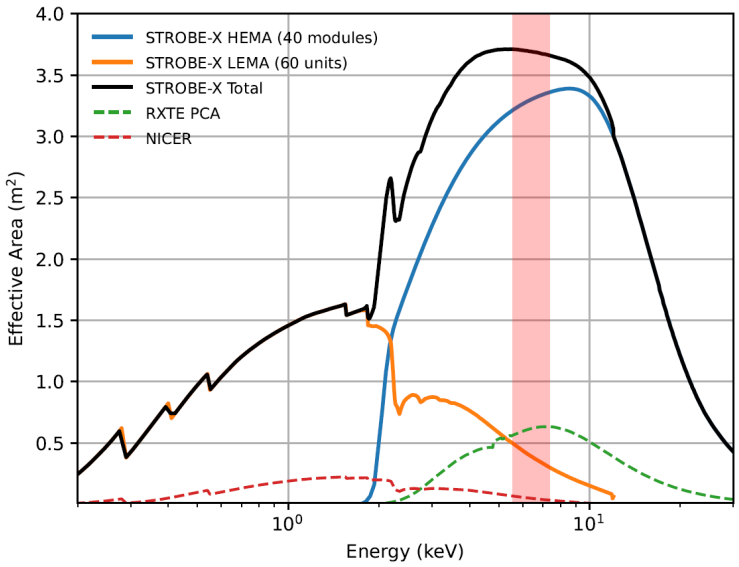

Figure 3. STROBE-X effective area, showing LEMA, HEMA individually and the total of the pointed instruments. For comparison, NICER and RXTE – the previous high-throughput missions in those energy bands – are shown on the same scale, illustrating the transformational increase in collecting area achieved. The pink shaded bar highlights the critical Fe-K line region.

bench for the entire instrument suite, with HEMA attached as panels to the bench side and the WFM mounted on the top. The structure is constructed in two halves to increase redundancy, reduce the size of the assembly and test fixtures, and allow parallelization in assembly, integration, and test flow.

HEMA is a large-area, collimated instrument operating in the 2–30 keV energy range, complementing LEMA by providing huge collecting area in the Fe-K line region and above.[9,10] The instrument leverages the technologies of large-area SDDs and capillary plate collimators to enable several square meters to be deployed in space within reasonable mass, volume, and power budgets. Its 1° FoV is co-aligned with the LEMA FoV. HEMA's unprecedented collecting area is achieved through a modular and intrinsically highly redundant design. There are four HEMA panels, with two hosted on either side of each LEMA optical bench. Each HEMA panel hosts 10 (5×2) modules for a total of 40 modules or 640 detectors. The total $A_{\rm eff}$ is 3.4 m^2 at 8.5 keV and the energy resolution is 300 eV at 6.4 keV.

The WFM is a coded-aperture mask design with four camera pairs that give an instantaneous FoV of 4 sr (32% of the sky).[11] The detectors share the SDD technology of HEMA but use finer anode pitch to provide imaging capability. The nominal energy band is 2–50 keV, with an energy resolution of 300 eV and a source localization accuracy of 1 arcmin. All observed events will be sent to the ground, which makes WFM a powerful facility both for transient identification and long-term monitoring of the X-ray sky. Source detection and transient triggering are performed onboard, allowing the WFM to issue prompt burst alerts to the community and trigger autonomous repoint requests for the pointed instruments to allow them to get on the source within minutes of a transient detection (actual time depends on the length of slew).

Table 1 summarizes the instrument performance parameters.

4. MISSION OPERATIONS DESIGN

The STROBE-X mission operations concept is based on heritage and lessons learned from the Swift mission.[1] The mission operations architecture connects the mission operations center (MOC) with the ground network, space-to-space network, science operations center (SOC), general coordinates network, and the spacecraft. The SOC uses a Swift-like planning model for producing an observing schedule that integrates present observatory status with priority decisions five times per week which then generates a target schedule and selected ToOs that

Table 1. Instrument characteristics

Quantity	**LEMA**	**HEMA**	**WFM**
Bandpass	0.2–12 keV	2–30 keV	2–50 keV
Effective Area	16,000 cm^2	34,000 cm^2	364 cm^2
Energy Resolution	85 eV (@ 1keV)	<300–500 eV (@ 6.4 keV)	300 eV (@6.4 keV)
Number of Units	60 XRCs	40 modules	4 camera pairs
FoV	$4'$ (FWHM)	1° (FWHM)	32% of sky (half coded)
Absolute Time Accuracy	200 ns	7 μs	24 μs
Count Rate on 1 Crab	111,000 c/s	104,000 c/s	380 c/s

are forwarded to the MOC for execution. The MOC integrates the desired observation schedule, communication plan, and ToO data products into its S/C command upload sequence. The SOC also processes the science data for distribution via the HEASARC and through an intermediate self-hosted quicklook page. The SOC will process ToO requests from the community, which can be submitted by web page, API, or automatically via transient brokers based on pre-selected target criteria. Based on urgency, ToOs can either be uplinked to the spacecraft in real-time utilizing a safe SOC-MOC interface which provides necessary information needed to create a ToO command to the MOC in a standard format or placed into the short-term plan for future scheduling.

STROBE-X is currently under review for the 2023 Astrophysics Probe mission call. Downselect for Phase A is anticipated in the first quarter of 2025.

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