STROBE-X: Capturing the Universe in Motion

Spectroscopic Time-Resolving Observatory for Broadband Energy X-rays

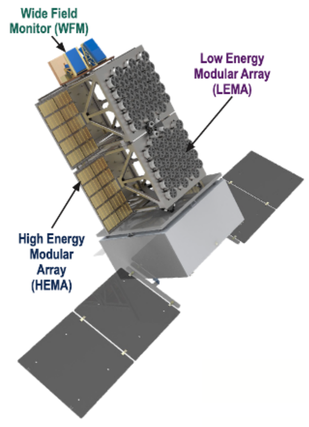
STROBE-X

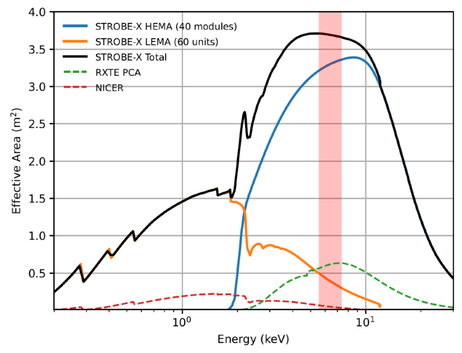
https://strobe-x.org

Paul S. Ray,[a,*] Peter W. A. Roming,[b] Andrea Argan,[c] Zaven Arzoumanian,[d] David R. Ballantyne,[e] Slavko Bogdanov,[f] Valter Bonvicini,[g] Terri J. Brandt,[h] Michal Bursa,[i] Edward M. Cackett,[j] Deepto Chakrabarty,[k] Marc Christophersen,[a] Kathleen M. Coderre,[l] Gianluigi De Geronimo,[m,n,o] Ettore Del Monte,[c] Alessandra DeRosa,[c] Harley R. Dietz,[l] Yuri Evangelista,[c] Marco Feroci,[c] Jeremy J. Ford,[b] Cynthia Froning,[b] Christopher L.Fryer,[p] Keith C. Gendreau,[d] Adam Goldstein,[q] Anthony H. Gonzalez,[r] Dieter Hartmann,[s] Margarita Hernanz,[t] Anthony Hutcheson,[a] Jean in 't Zand,[h] Peter Jenke,[u] Jamie Kennea,[v] Nicole M. Lloyd-Ronning,[p] Thomas J. Maccarone,[w] Dominic Maes,[x] Craig B. Markwardt,[d] Malgorzata Michalska,[y] Takashi Okajima,[d] Alessandro Patruno,[t] Steven C. Persyn,[b] Mark L. Phillips,[b] Chanda Prescod-Weinstein,[z] Jillian A. Redfern,[b] Ronald A. Remillard,[k] Andrea Santangelo,[aa] Carl L. Schwendeman,[b] Clio Sleator,[a] James Steiner,[ab] Tod E. Strohmayer,[d] Jiri Svoboda,[i] Christoph Tenzer,[aa] Steven P. Thompson,[b] Richard W. Warwick,[l] Anna L. Watts,[ac] Colleen A. Wilson-Hodge,[ad] Xin Wu,[ae] Eric A. Wulf,[a] and Gianluigi Zampa[g]

A Probe Class Mission for the 2030s

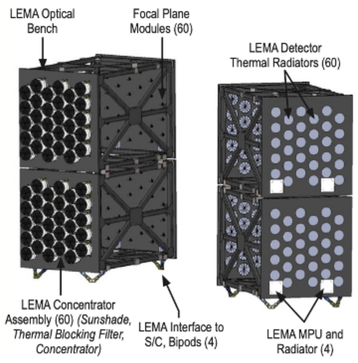
- **STROBE-X is a game changing X-ray mission devoted to time domain and multi-messenger (TDAMM) astrophysics and high throughput spectroscopy, addressing all of NASA's Astrophysics Division science objectives.**
- Its Wide Field Monitor (WFM) captures and characterizes transients and variability on short and long timescales and provides triggers for autonomous followup.
- The enormous collecting area of the pointed instruments (LEMA and HEMA) provide unique access to precision measurements of physical conditions in nature's most extreme environments.
- Simultaneous broadband coverage provides measurements that constrain absorption, thermal emission, comptonization and reflection spectra and their temporal relationships
- Serves the broad TDAMM and X-ray astrophysics community with rapid alerts (arcmin localizations), and rapid response to TOOs on a range of timescales





- Two pointed instruments (LEMA & HEMA) together covering 0.2–30 keV X-ray band
- Wide Field Monitor provides transient alerts and full sky source monitoring (2–50 keV) giving arcmin positions of transients
- Highly modular design improves reliability at reduced cost and allows easy scaling, and integration schedule flexibility
- LEO orbit (<15° inclination) reduces background and radiation damage
- Rapid slewing agile spacecraft from Lockheed Martin
- Pointed instruments can observe >3 sources per orbit (avoiding Earth occultations)
- Autonomously respond to onboard or ground transient alerts and begin observing in <9–14 min (depends on angle from boresight)
- Broad field of regard (entire sky outside 45° Sun exclusion zone)
- High rate downlinks (Ka band) to ground stations
- Low-latency alerts and TOO commanding via space-to-space link

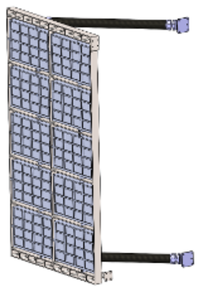
Low-Energy Modular Array (LEMA)



- **High throughput, low background spectral timing in the 0.2–12 keV band**
- Concentrator optics scaled up from NICER (diameter and focal length)
  - 4' FoV (non-imaging)
- SDDs and electronics inherited from NICER
  - ΔE = 85 eV @ 1keV
- Composite optical bench designed by BAE Inc.
- 2x30 concentrators,1.6 m² total effective area

Quantity	LEMA	HEMA	WFM
Bandpass	0.2 to 12 keV	2 to 30 keV	2 to 50 keV
Effective area	16,000 cm²	34,000 cm²	364 cm²
Energy resolution	85 eV (@ 1 keV)	<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 deg (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

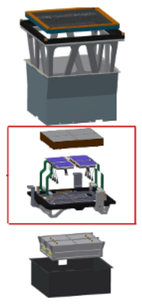
High-Energy Modular Array (HEMA)



Panel (1 of 4)

- **Large area 2–30 keV collimated spectral timing instrument**
- Effective area 3.4 m² at 8.5 keV
- Field of View: 1 degree FWH
- Large-area silicon drift detectors (SDDs) with lead-glass microchannel plate collimators
- 4 fixed (not deployable) panels
- Absolute timing accuracy: 7 μs
- Energy resolution: < 500 eV at 6 keV

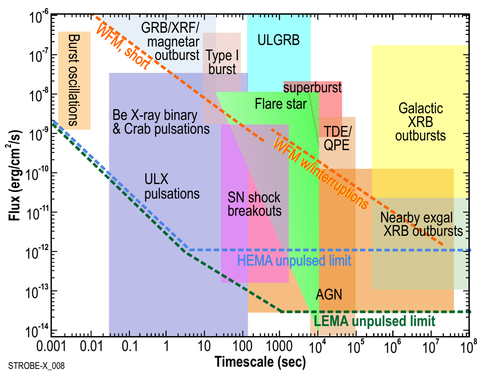
Wide Field Monitor (WFM)



- **4 camera pairs combine to view ⅓ of the sky at a time**
- 1.5D coded mask camera with similar SDDs to HEMA
- Energy range: 2–50 keV
- ΔE = 300 eV
- All data come down in event mode
- Onboard processing can produce alerts

Why a Flexible, High-Throughput X-ray Observatory?

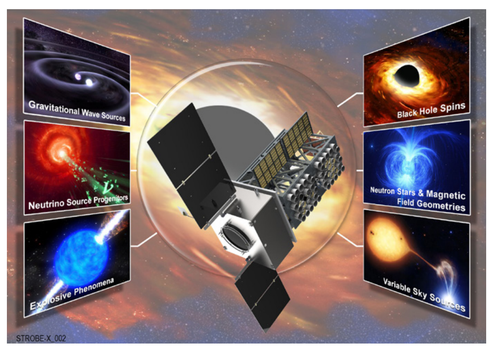
- The high-energy sky is highly dynamic – requires catching the right source at the right time necessitates both wide field monitoring and the ability to repoint quickly (as RXTE, Swift and NICER have demonstrated)
- This is a critical capability in the era of time domain and multi-messenger (TDAMM) astronomy
- Timing is sensitive to geometry at size scales that imaging can't approach
- Large areas with low dead time access the shortest timescales
- Both soft and hard X-ray bands are needed to accurately measure the continuum spectral shape, constrain absorption, and understand the relationship between thermal and non-thermal components



STROBE-X provides the X-ray eyes on the dynamic universe, observing transient sources and phenomena spanning eight orders of magnitude in flux and 12 orders of magnitude in timescale. The colored regions show the areas of flux-timescale phase space occupied by various classes of transients. The dashed lines show the sensitivity limits for the various instruments. The HEMA and LEMA lines become horizontal at the background systematics limit for unpulsed sources. For coherent pulsations, their sensitivity continues to improve with time indefinitely.

Driving Science Goals

- **Multi-messenger**: Detect and localize gravitational wave and neutrino source progenitors and counterparts to understand their jets, compact remnants, and ejecta.
- **Time DomainAstronomy of Explosive Transients:** Discover, follow up, and provide the X-ray characterization of new events to determine what powers explosive phenomena.
- **Gravity and Extreme Physics:** Probe the extremes of relativistic and particle astrophysics by observations of black hole spins across the mass spectrum and neutron star equation of state, surface configuration, and magnetic field geometries.
- **The Dynamic Universe**: Provide the X-ray view of the variable sky with wide-field monitoring and broadband spectroscopy.



History of STROBE-X

The Rossi X-ray Timing Explorer (RXTE) [13] was a highly successful [14] large-area X-ray timing mission with broad energy coverage, which operated from 1999 to 2012.

Multiple efforts have been made to build on that success:

AXTAR [6] was studied in advance of Astro2010 pushing for "X-ray timing of compact objects that combines very large collecting area, broadband spectral coverage, high time resolution, highly flexible scheduling, and an ability to respond promptly to time-critical targets of opportunity".

LOFT [7] was developed in Europe taking advantage of silicon drift detectors (SDDs) that improved performance. It was selected for an ESA M3 assessment phase study, but eventually not selected for implementation..

NICER [9] was selected as an MOO and operated on ISS from 2017–2025, doing X-ray timing in a softer band with concentrating optics for low backgrounds.

Technologies from both LOFT and NICER were combined into STROBE-X, which was awarded a probe-class concept study in preparation for Astro2020 [11]

In response to the strong recommendations of Astro2020 to implement a probe class X-ray or Far IR mission and to pursue a program of Time Domain and Multi-Messenger (TDAMM) astrophysics, NASA put out a call for probe class missions in 2023. STROBE-X [1,2,3,4,5] was one of the X-ray missions submitted to that call.

In the probe competition, STROBE-X received a Category 1 ranking and with low technical and cost risk, but was not selected for a Phase A study.

Updated Context

The science landscape for time-domain X-ray astronomy has changed significantly since the probe proposals were submitted in 2023.

For some high-energy transient science, other missions have recently been launched or proposed, while others have been canceled or ended. Without a new mission, a major gap will exist for a mission that can detect X-ray transients and rapidly respond with high-throughput observations that can do detailed time-resolved spectroscopy and study fast variability.

- The X-ray probe class mission concept that was selected (**AXIS**) was a high resolution imager optimized to study to distant universe. NASA recently announced that AXIS will not go forward, leaving no NASA X-ray mission concept currently under development.
- The **NICER** mission ceased science operations in 2025, ending a critical high-throughput timing mission.
- The **Swift** mission will re-enter in 2026, ending the mission.
- The **THESEUS** mission was not selected by ESA for development.
- NASA **SMEX** proposals will be submitted in September 2026, and at least 2 concepts have wide field X-ray/gamma-ray capabilities, but no guarantee one will be chosen
- **SVOM** and **Einstein Probe** are currently operating providing X-ray sky monitoring capabilities, but not open data.
- The Chinese-led **eXTP** is expected to launch in 2030 with significant X-ray imaging and polarimetry capabilities.
- **Athena,** the next X-ray flagship mission, is expected to launch around 2037

A Broad Portfolio of Astrophysics

Some of the many additional ways STROBE-X will broadly across astronomy:

Supernovae & GRBs
- NGC 2700-like shock breakouts from Type Ibc out to 20 Mpc
- Near-all-sky sensitivity to AT2018cow type events out to ~100 Mpc
- Near-instantaneous GRB positions of 1'
- X-ray based redshifts from prompt emission for a small subset of GRBs
- Re-open the field of X-ray flashes, which may be ultra-high-*z* GRBs, off-axis local GRBs, or some combination of the two

AGN
- Reverberation mapping of tori
- Timing masses of 100 AGN with Wide Field Monitor, potentially thousands with LEMA
- Greater all-sky sensitivity than eROSITA to Compton thick AGN with WFM emission line survey
- All sky survey for *z*>4 blazars
- Discovery of jetted tidal disruptions and monitoring of all classes of tidal disruptions
  Continuous monitoring of bright blazars

X-ray Binary Accretion Physics
- Timing measurements of disk winds
- Correlation with fast timing in other bands to map out jet acceleration
- Spectral timing of quasi-periodic oscillations and testing of the Lense-Thirring model

Magnetized accretors
- ULX pulsations out to ~20 Mpc
- Accreting pulsars with good signal to noise for individual pulses

Stellar Coronae
- Discovery of ~100 hard X-ray flares per year (i.e the most extreme events), with automated slewing for LEMA to look with high time resolution at their spectral evolution
  Triggering of searches for exoaurorae

Supernova remnants
- Detailed abundances for large sample of Galactic and Magellanic Cloud SNRs to do supernova typing retroactively

Binary Stellar Evolution
- Build up large sample of X-ray binary outbursts, expecting ~5 new black hole binaries per year, and probing the short period end of the distribution
- Develop a large enough sample of black holes to test the "mass gap" between BHs and NSs
- Capability to detect 0.4% pulsations in 100 seconds for 150 mCrab neutron star binaries - likely will fill in spin period distribution even for nominally non-pulsed sources
- Orbital and spin period evolution for high mass X-ray binaries, even out to 2 Mpc

Isolated Neutron Stars
- Contribute to Pulsar Timing Array for pulsars behind high electron columns
- Measure periods and magnetic fields of new isolated neutron stars from eROSITA

Clusters and Groups of Galaxies:
- LEMA collecting area allows 30% metallicity measures for *z*=1.5 clusters
- Local compact groups also can have metallicity measured

Axions
- Cluster spectroscopy
- Neutron star cooling

Comets
- Measure abundances from charge exchange for several comets per year

References

[1] Ray, P. S., Roming, et al. 2024, "*Spectroscopic Time-Resolving Observatory for Broadband Energy X-rays: mission overview*" JATIS 10, 042504 (doi: 10.1117/1.JATIS.10.4.042504)

[2] Gendreau, K. C., Maes, D., Remillard, R. A., Ray, P. S., Arzoumanian, Z., Markwardt, C., & Okajima, T. 2024, "*STROBE-X low-energy modular array (LEMA) instrument*" JATIS 10, 042506 (doi: 10.1117/1.JATIS.10.4.042506)

[3] Remillard, R. A., Hernanz, M., Zand, J. in't ., Ray, P. S., et al. 2024, "*The STROBE-X wide field monitor instrument*" JATIS 10, 042505 (doi: 10.1117/1.JATIS.10.4.042505)

[4] Hutcheson, A. L., Feroci, M. et al. 2024, "*Spectroscopic Time-Resolving Observatory for Broadband Energy X-ray high-energy modular array*" JATIS 10, 042503 (doi: 10.1117/1.JATIS.10.4.042503)

[5] De Geronimo, G., Ray, P. S., Wulf, et al. 2024, "*Front-end application-specific integrated circuits for the Spectroscopic Time-Resolving Observatory for Broadband Energy X-rays High Energy Modular Array and Wide Field Monitor detectors: concept and design*" JATIS 10, 042502 (doi: 10.1117/1.JATIS.10.4.042502)

[6] Ray, P. S., Chakrabarty, D., Wilson-Hodge, C. A., et al. 2010, "*AXTAR: mission design concept*" SPIE 7732, 773248 (doi: 10.1117/12.857385)

[7] Feroci, M., et al. 2014, "*The Large Observatory for x-ray timing*" SPIE 9144, 91442T (doi: 10.1117/12.2055913)

[8] Wilson-Hodge, C. A., Ray, P. S., Chakrabarty, D., Feroci, M., et al. 2016, "*Large Observatory for x-ray Timing (LOFT-P): a Probe-class mission concept study*" SPIE 9905, 99054Y (doi: 10.1117/12.2232944)

[9] Gendreau, K., et al. 2016,"*The Neutron star Interior Composition Explorer (NICER): design and development*" SPIE 9905, 99051H (doi: 10.1117/12.2231304)

[10] White, N. E. Et al. 2026, "*XTRA: The X-ray TRansient Array*" Proc. SPIE, in press

[11] Ray, P. S. et al. 2019, "*STROBE-X: X-ray Timing and Spectroscopy on Dynamical Timescales from Microseconds to Years*" arXiv:1903.03035

[12] Feroci, M., et al. 2016, "*The LOFT mission concept: a status update*" SPIE 9905, 99051R (doi: 10.1117/12.2233161)

[13] Bradt, Rothschild & Swank 1993, "*X-ray timing explorer mission*" A&AS, 97, 355

[14] van der Klis, M. 2006, "*Rapid X-ray variability*" in Compact Stellar X-ray Sources, eds. W. Lewin & M. van der Klis, Cambridge Astrophysics Series 39 (Cambridge University Press), 39 (arXiv:astro-ph/0410551)

Affiliations

* paul.s.ray3.civ@us.navy.mil
[a]Space Science Division, U.S. Naval Research Laboratory, Washington, District of Columbia, United States
[b]Southwest Research Institute, San Antonio, Texas, United States
[c]INAF – Istituto di Astrofisica e Planetologia Spaziali, Roma, Italy
[d]NASA's Goddard Space Flight Center, Greenbelt, Maryland, United States
[e]Georgia Institute of Technology, Atlanta, Georgia, United States
[f]Columbia University, Columbia Astrophysics Laboratory, New York, New York, United States
[g]Istituto Nazionale di Fisica Nucleare, Trieste, Italy
[h]SRON Netherlands Institute for Space Research, Leiden, The Netherlands
[i]Astronomical Institute of the Czech Academy of Sciences, Prague, Czech Republic
[j]Wayne State University, Department of Physics & Astronomy, Detroit, Michigan, United States
[k]Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States
[l]Lockheed Martin Co., Littleton, Colorado, United States
[m]Univeristy of Michigan, Department of Nuclear Engineering and Radiological Sciences, Ann Arbor, Michigan, United States
[n]Stony Brook University, Electrical and Computer Engineering, Stony Brook, New York, United States
[o]DG Circuits, dgcircuits.com, Syosset, New York, United States
[p]Los Alamos National Laboratory, Los Alamos, New Mexico, United States
[q]Universities Space Research Association, Huntsville, Alabama, United States
[r]University of Florida, Department of Astronomy, Gainesville, Florida, United States
[s]Clemson University, Department of Physics and Astronomy, Clemson, South Carolina, United States
[t]Institute of Space Sciences (ICE-CSIC) and IEEC, Campus UAB, Bellaterra (Barcelona), Spain
[u]University of Alabama in Huntsville, Huntsville, Alabama, United States
[v]The Pennsylvania State University, Department of Astronomy and Astrophysics, University Park, Pennsylvania, United States
[w]Texas Tech University, Department of Physics & Astronomy, Lubbock, Texas, United States
[x]BAE Systems Space & Mission Systems Inc., Boulder, Colorado, United States
[y]Polish Academy of Sciences, Space Research Center, Warszawa, Poland
[z]University of New Hampshire, Department of Physics and Astronomy, Durham, New Hampshire, United States
[aa]Eberhard Karls Universität, Tübingen, Germany
[ab]Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts, United States
[ac]University of Amsterdam, Anton Pannekoek Institute for Astronomy, Amsterdam, The Netherlands
[ad]NASA's Marshall Space Flight Center, Astrophysics Branch, Huntsville, Alabama, United States
[ae]University of Geneva, Department of Nuclear and Particle Physics, Geneva, Switzerland

DISTRIBUTION STATEMENT A. Approved for public release: distribution is unlimited.

Basic research in X-ray astronomy at NRL is supported by ONR 6.1 funding.