The Large Observatory For X-ray Timing Probe (LOFT-P): A NASA Probe-Class Mission Concept

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LOFT-P is a probe-class X-ray observatory designed to work in the 2–30 keV band with huge collecting area ($> 10\times$ NASA's highly successful *RXTE*) and good spectral resolution (<260 eV). It is optimized for the study of matter in the most extreme conditions found in the Universe and addresses several key science areas including:

- Probing the behavior of matter spiraling into black holes (BHs) to explore the effects of strong gravity and measure the masses and spins of BHs.
- Using multiple neutron stars (NSs) to measure the ultradense matter equation of state over an extended range.
- Continuously surveying the dynamic X-ray sky with a large duty cycle and high time-resolution to characterize the behavior of X-ray sources over a vast range of time scales.
- Enabling multiwavelength and multi-messenger study of the dynamic sky through cross-correlation with high-cadence time-domain surveys in the optical and radio (LSST, LOFAR, SKA pathfinders) and with gravitational wave interferometers like LIGO and VIRGO.

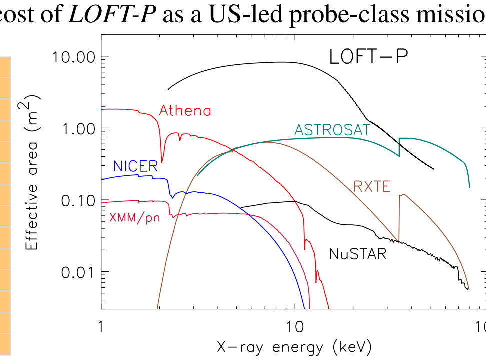
Detailed simulations[2] have demonstrated that an order of magnitude larger collecting area than *RXTE* (i.e., >6 m^2) is required to meet these BH and NS objectives, and a previous engineering study[3] has shown that such an instrument is too large for the Explorer (EX) class and instead requires a probe-class mission.

LOFT-P is adapted from a mission concept that has been under study in both the Europe and the US since 2010 [1]. It comprises two instruments. The Large Area Detector (LAD) consists of collimated arrays of silicon drift detectors (SDDs) with a 1-degree field of view and a baseline peak effective area of 10 m^2 at 8 keV, optimized for submillisecond timing and spectroscopy of NSs and BHs. The sensitive Wide Field Monitor (WFM) is a 2–50 keV coded-mask imager (also using SDDs) that acts as a trigger for pointed LAD observations of X-ray transients and also provides nearly continuous imaging of the X-ray sky with a large instantaneous field of view. The baseline mission specifications are shown in the table below, along with a figure comparing the LAD effective area to other missions.

The technical readiness underlying the *LOFT-P* concept is already high. *LOFT-P* uses large-area SDD technology originally developed for the ALICE-D4 experiment on the CERN Large Hadron Collider. The lead-glass collimators are well studied, with commercial manufacturing capability in Europe (Photonis), Japan (Hamamatsu), and the US.

Cost estimate. Based on the detailed 32-month Assessment Phase (Phase A) study of M-class *LOFT* for the ESA M3 competition in 2013, we estimate a US probe-class mission cost for *LOFT-P* of $770M, incorporating full lifecycle costs including labor, instruments, spacecraft, launch and 3 years of operations. In May 2016 the Advanced Concepts Office at NASA MSFC will perform a preliminary study to verify the cost of *LOFT-P* as a US-led probe-class mission.

Parameter	LAD	WFM
Detector Type	Silicon Drift Detector	Silicon Drift Detector
Number of Units	140 Modules x 16 Detectors/Module	5 Units x 2 Cameras/Unit
Effective Area	10 m^2 (at 8 keV)	364 cm^2 per Unit
Mask	—	0.25 x 14 mm elements (25% open)
Energy Range	2–30 keV (30–80 extended)	2–50 keV (50–80 extended)
Energy Resolution	<260 eV (<200 eV single-anode events)	<500 eV @ 6 keV
Spatial Resolution	—	5 arcmin x 5 arcmin
Field of View	1°	>4 sr (at >20% effective area)
Background	1000–3000 cts/s	550 cts/s per Unit
Time Resolution	10 μs	10 μs (event-mode)
Typical Data Rate (w/compression)	200/1000 kbps (100/500 mCrab)	425 kbps (event mode)
Mass (CBE w/contingency)	1300 kg	130 kg
Power (CBE w/contingency)	1100 W	100 W



Strong gravity and black hole spin. Unlike the small perturbations of Newtonian gravity found in the weak-field regime of general relativity (GR), strong-field gravity results in gross deviations from Newtonian physics and qualitatively new behavior for motion near compact objects, including the existence of event horizons and an innermost stable circular orbit (ISCO). *LOFT-P* observations will probe strong gravitational fields of NSs and BHs in a way that is complementary to gravitational wave interferometers like LIGO and VIRGO. Accretion flows and the X-ray photons they emit are "test particles" that probe the stationary spacetimes of compact objects, whereas gravitational waves carry information about the dynamical evolution of these spacetimes. As a result, *LOFT-P* observations will allow mapping the stationary spacetimes of black holes and testing the no-hair theorem [2]. In GR, only two parameters

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[2] http://sci.esa.int/jump.cfm?oid=53447
[3] http://pcos.gsfc.nasa.gov/studies/rfi/Ray-Paul-AXTAR-RFI.pdf

(mass and spin) are required to completely describe an astrophysical BH, and the X-rays originating in the strong gravity regions necessarily encode information about these fundamental parameters.

LOFT-P observations of accreting stellar-mass BHs will be unique in providing three independent measurements of each BH spin from high-frequency quasi-periodic oscillations (HFQPOs), relativistic reflection modelling of Fe (and other) lines, and disk continuum spectra, each using techniques with differing systematic uncertainties. In those systems in which HFQPOs have already been detected with $\sim 5\%$ rms amplitude by *RXTE*, deeper observations with *LOFT-P* will allow detections of the 5–10 additional QPO peaks predicted by theory. This will identify their frequencies with particular linear or resonant accretion disk modes; this will be possible once a spectrum of modes is observed, instead of just a pair. *LOFT-P*'s timing capabilities can also test whether the correct spins have been obtained by reverberation mapping of the X-ray reflection in X-ray binaries and AGN (with better S/N than *Athena*).

Properties of ultradense matter. How does matter behave at the very highest densities? This seemingly simple question has profound consequences for quantum chromodynamics and for compact object astrophysics. The equation of state (EOS) of ultradense matter (which relates density and pressure) is still poorly known, and exotic new states of matter such as deconfined quarks or color superconducting phases may emerge at the very high densities that occur in NS interiors. This regime of supranuclear density but low temperature is inaccessible to laboratory experiments (where high densities can only be reached in very energetic heavy ion collisions), but its properties are reflected in the mass-radius (M-R) relation of NSs. Consequently, measurement of NS M and R is the crucial ingredient for determining the ultradense matter EOS.

LOFT-P will obtain M and R measurements by fitting energy-resolved oscillation models to the millisecond X-ray pulsations arising in a hot spot from rotating, accreting NSs. The detailed pulse shape is distorted by gravitational self-lensing, relativistic Doppler shifts, and beaming in a manner which encodes M and R. Detailed modeling of the pulse profile can extract M and R separately [3]. Measurements of both M and R for three or more NSs, made with $\approx$5% precision, would definitively determine the EOS of ultradense matter, while measurement of a larger number of NSs with $<$10% precision would still place strong constraints. The recently approved *NICER* mission will apply this same technique to faint rotation-powered pulsars, a different class of NSs. This is complementary to *LOFT-P* rather than duplicative. A key difference between the NSs targeted by *NICER* and *LOFT-P* is that the *NICER* targets generally rotate more slowly ($<$300 Hz) than the *LOFT-P* targets ($>$600 Hz). As a result, *NICER* observations cannot fully exploit Doppler effects to break degeneracies between M and R, making precise and uncorrelated measurements more difficult. *NICER* will obtain precise ($<$5%) determinations of R for only 1–2 sources; this is unlikely to be sufficient to solve the EOS problem, since multiple measurements are required to measure the slope of the M-R curve and, hence, of the pressure-density relation that describes the EOS. Combining M-R measurements from *NICER* and *LOFT-P* will triple the sample size.

The M-R relation of neutron stars can also be probed with magnetar oscillations. Like with the HFQPOs, by dramatically improving the collecting area, enough frequencies should be found to allow mode identification. Given the relative precision of timing calibration to response matrix calibration, timing-based models should eventually allow the highest precision measurements possible.

Observatory science As a flexible observatory with superb spectral-timing capabilities and wide field coverage of the sky over a broad range of timescales, *LOFT-P* will serve a large user community and make significant scientific impact on many topics in astrophysics. The LAD will study accretion physics, jet dynamics (especially in conjunction with timing studies in the infrared that will be possible on medium-sized telescopes), and disk winds (taking advantage of the high throughput and high spectral resolution which will allow very rapid detection of the turn-on of a disk wind).

The WFM's combination of angular resolution, sensitivity, spectral resolution and *instantaneous* wide-field coverage will enable studies of black hole transients, tidal disruption events, and gamma-ray bursts too faint for current instrumentation. It will also enable instant spectroscopic follow-up of these events, as the positional accuracy will be smaller than the fields of view of modern integral field units. The WFM's mission-long survey of the sky in Fe Kα will be more sensitive to Compton thick AGN than *eROSITA*.

The WFM will be unique as a discovery machine for the earliest stages of supernova shock breakouts by working in the X-rays, and having the sensitivity and instantaneous field of view to have an expected detection rate of a few breakouts per year within 20 Mpc. This will allow much more rapid spectroscopic follow-up than other means of discovering supernovae, allowing crucial studies of the early stages of the explosions that can be used to probe details of the explosion mechanisms and the binarity of supernova progenitors. *LOFT-P* will be ideal for detecting and localizing X-ray counterparts to gravitational wave sources, fast radio bursts, and optical transients in the era of LSST.

References. [1] Feroci, M. et al. 2014, Proc. SPIE 9144, 91442T; [2] Psaltis, D. 2008, Liv. Rev. Rel., 11, 9; [3] Watts et al. 2016, Rev. Mod. Phys., in press (arXiv:1602.01801)

For more information see:
`https://sites.google.com/site/loftpmissionpage/`