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LOFT: the Large Observatory For x-ray Timing

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Abstract. High-time-resolution X-ray observations of compact objects provide direct access to strong-field gravity, black hole masses and spins, and the equation of state of ultradense matter. A 10 m^2-class instrument in combination with good spectral resolution is required to exploit the relevant diagnostics and answer two fundamental questions of ESA´ s Cosmic Vision Theme *Matter under extreme conditions*, namely: does matter orbiting close to the event horizon follow the predictions of general relativity ? What is the equation of state of matter in neutron stars ? Thanks to an innovative design and the development of large monolithic Silicon Drift Detectors, the Large Area Detector (LAD) on board the Large Observatory For x-ray Timing (LOFT) will afford an effective area of $\sim$ 10 m^2 (more than an order of magnitude larger than X-ray detectors of the past and present generations) in the 2-30 keV range (up to 80 keV in extended mode), with a spectral resolution of <260 eV over its entire band. The Wide Field Monitor on board LOFT will monitor about 1/4 of the X-ray sky at any one time, identifying specific source states and discovering transient events and sources to be followed up with LAD pointed observations and other astronomical facilities. LOFT will revolutionize the study of collapsed objects in our galaxy and of the brightest supermassive black holes in active galactic nuclei, yielding unprecedented information on strongly curved spacetimes and matter under extreme conditions. LOFT will also be operated as an observatory to study thousands of X-ray sources of different classes and address a variety of aspects of their physics.

Key words. accretion, accretion disks - black hole physics - dense matter - gravitation - instrumentation: detectors - stars: neutron

1. Introduction

The Large Observatory For x-ray Timing (LOFT) is a medium-size high energy astrophysics mission which is currently being studied within the ESA M3 Cosmic Vision program. Preselected in February 2011, LOFT is one of five proposed missions that compete for a launch opportunity in the 2022-2024 time frame; final selection will take place in 2014. LOFT is designed to address the *Matter under extreme conditions* theme of ESA´ s Cosmic Vision program, and in particular to probe *gravity theory in the strong field environment of black holes and other compact objects* (hereafter Strong Gravity) and *the state of matter at supra-nuclear energies in neutron stars* (hereafter Dense Matter). To this aim LOFT will exploit the techniques of X-ray timing and spectroscopy with unprecedented throughput, thanks to the combination of extremely large effective area ($\sim$10 m^2 at 8 keV, about 20 times larger than that of the Rossi X-ray

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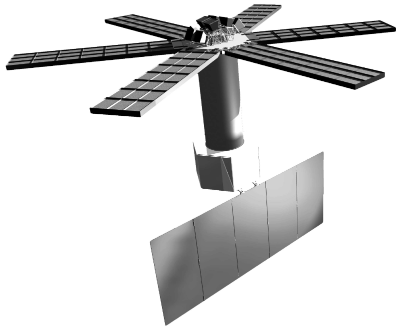

Fig. 1. The LOFT Satellite. The LAD consists of the 6 deployable panels covered by SDDs. The WFM, comprising 10 coded-mask cameras is located on the top of the optical bench. The bus and solar panels are also displayed.

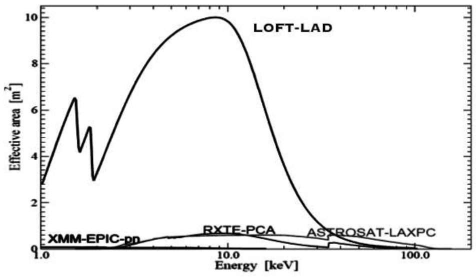

Fig. 2. Effective area of the LAD as a function of energy. The effective area of some the largest X-ray observatories is also displayed on the same scale.

Timing Explorer PCA) and fine spectral resolution (200-260 eV at 6 keV) of its Large Area Detector (LAD). The Wide Field Monitor (WFM) will observe about 1/4 of the X-ray sky at any one time, monitoring source states and catching transient events and sources to be followed up with LAD pointings (Feroci et al. 2012), as well as other facilities. The satellite will be injected in a low equatorial orbit by a Soyuz launcher; its nominal lifetime will be 4 yr, plus a 1 yr extension. The LOFT payload consortium comprises groups from 11 ESA member states (Czech Republic, Denmark, Finland, France, Germany, Italy, The Netherlands, Poland, Spain, Switzerland, United Kingdom), with support of scientists from Brazil, India, Japan and the US.

1.1. The Large Area Detector

The LAD is a collimated non-imaging instrument operating in the 2-30 keV energy band. Its presents design envisages six panels hosting a total of ~2000 Silicon Drift Detectors (SDDs) each with a geometric area of 76 cm^2. This translates into an effective area for scientific observations reaching ~10 m^2 at 8 keV (see Fig. 2). The main operating energy range of the LAD is 2-30 keV, plus the 30-80 keV extended energy range (Zane et al. 2012). The energy resolution at 6 keV is 200 eV for 40% of the events, and 260 eV for the remaining events. The lead-glass collimators that are overlaid on top of the LAD SDDs collimators use micro-channel plate technology (Fraser et al. 2010) and efficiently limit the field of view (FOV) to $\sim$ 1 deg up to energies of ~30-40 keV. Higher energy photons from the Cosmic X-ray Background (CXB) leaking through the collimators gives the largest contribution to the LAD background. The Crab event rate in the LAD is $\sim 2.4 \times 10^5$ cts/s.

1.2. The Wide Field Monitor

In its current design, the WFM consists of 10 cameras, each equipped with a coded-mask and 4 SDDs (similar to the LADs, but optimized for imaging). The WFM operates in the 2-50 keV energy range. The field of view of the WFM is a roughly rectangular 180x90 deg^2 region, with an additional extension in the anti-Sun direction (Fig. 3). The WFM on-board software is designed to identify and localize bright high energy events, such as gamma ray bursts, magnetar bursts/flares, and other high-energy transients, with ~arcmin accuracy. The position and time of these events will be broadcasted to the ground using a VHF system within 30 s from discovery (Brandt et al. 2012), so that fast-response follow-up observations with other facilities can be triggered.

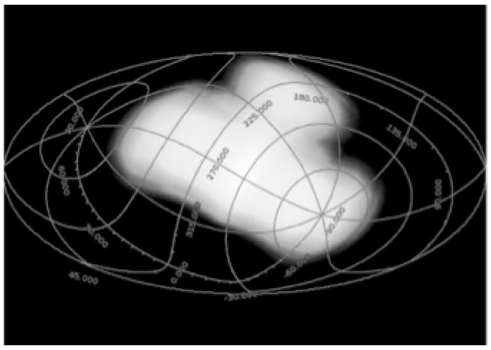

Fig. 3. WFM field of view in galactic coordinates, during a LAD observation of the galactic center.

2. LOFT Science

Matter that moves in the highly curved space-time close to neutron stars and black holes attains speeds that are a significant fraction of the speed of light. The gravitational energy that is released by accretion is usually emitted at X and gamma-ray energies. Dynamical timescales as well as rotational periods can be as short as $\sim$1 ms or less. High speed, high throughput timing measurements are especially powerful diagnostics of such relativistic conditions. Moreover X-ray spectroscopy with *medium resolution* ($E/\Delta E$ of several tens) is well suited to study spectral features which are made broad by the very large energy shifts involved. LOFT is designed to fully exploit the potential of these diagnostics. About 50% of the observing time will be devoted to the top level science goals, *i.e.* dense matter and strong gravity; for the other half of the time LOFT will address a variety of themes in high energy astrophysics and operate like an observatory.

2.1. Dense Matter

Understanding the properties of ultradense matter is one of the most challenging problems in contemporary physics. At densities exceeding that of atomic nuclei, exotic states of matter such as Bose condensates or hyperons may appear; phase transitions to matter characterized by different pairing patterns of quarks may take place at higher still densities. Particle accelerators and heavy-ion collision experiments provide information on the high temperature regime of the so-called *Quantum Chromodynamics Diagram*, but only neutron stars can probe the *zero temperature* regime relevant to these transitions. The relation between the neutron star mass and radius (M-R) is a powerful probe of the equation of state (EoS) of dense matter (for a review see Lattimer & Prakash 2007). The EoS at supranuclear density involves a great deal of interest also in astrophysics: for instance it influences gravitational collapse and the gravitational wave signal from coalescing binaries consisting of two neutron star or a stellar-mass black hole and a neutron star.

Apart from redshifts of any narrow atmospheric lines (feasible for slowly rotating neutron stars only), techniques devised to constrain the M-R relations are based primarily on accurate time-resolved and high-throughput broadband spectral measurements. In $\sim$25 accreting neutron stars in low mass X-ray binaries, spins in the few ms range have been measured through burst oscillations and/or coherent pulsations. Owing to their fast rotation and strong gravitational field, the signal from the surface hot spots producing the pulsations is affected by relativistic beaming, time dilation, red/blue-shifts, light bending and frame dragging and thus encodes information on the neutron stars M and R (see *e.g.* Morsink & Leahy 2011). LOFT will observe these signals with extremely high signal to noise, and measure M and R of accreting fast spinning neutron stars to an accuracy of 5% (Fig. 4).

LOFT will be able to cross-validate these results through the exploitation of different techniques. Since the highest spin a neutron star can sustain depends on its mass and structure, the fastest periods also place constraints on the EoS. LOFT will search for periodic signals with unprecedented sensitivity. Models indicate that the pulsation amplitude of fast spinning neutron stars in X-ray binaries may be as low as 0.1%, so the effective area of the LAD is needed to detect these pulsations in a typical observation of hundreds mCrab source. This, together with the discovery of a few intermit-

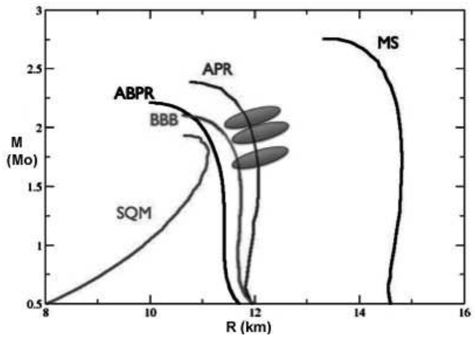

Fig. 4. By exploiting different techniques LOFT will measure masses and radii of neutron star with an accuracy of ~5% (ellipses). This will permit to obtain very high precision constraints on the dense matter EoS, and to distinguish even between EoS models that make similar predictions for the M-R relation (curves show some examples).

tent X-ray pulsars, with small pulse amplitudes over short periods of time, indicate that LOFT will build up a much better spin period distribution of accreting neutron stars than has been possible so far.

A different approach has recently emerged from the discovery of global seismic oscillations (GSOs) in the tens of Hz to kHz range from the magnetars hosted in Soft Gamma Repeaters during the rare and extremely luminous *giant flares* emitted by these sources. These GSOs are believed to arise from modes of oscillations in the magnetar crust and interior which are triggered by energetic flares; their frequencies can probe the star structure and EoS in a manner similar to the way earthquakes diagnose the structure of our planet. LOFT will detect and study GSOs for the first time in *intermediate flares*, shorter and less-energetic events from magnetars which are tens of times more frequent than giant flares. During its operational lifetime, LOFT will be able to detect GSOs from *intermediate flares*, down to amplitudes which are an order of magnitude lower than those seen up to now. This will open a new window in the study of neutron star structure through *asteroseismology*.

2.2. Strong Gravity

The second main science goal of LOFT is probing of strong-field gravity *in situ*, *i.e.* within several Schwarzschild radii of a compact object: this has the keen interest of both the physical and astrophysical communities. Rather than the very accurate measurements of small deviations from Newtonian physics possible in the Solar system and with radio pulsars in binary systems hosting two neutron stars, *in-situ* strong field measurements address the large deviations and qualitatively new effects General Relativity (GR) predicts close to compact objects. None of these have yet been verified, but initial indications may already have been seen (*e.g.* McClintock et al. 2011).

About 40 compact objects accreting matter in binary systems are now known to display variability arising in, and occurring at the (millisecond) dynamical timescales of their inner accretion flows: black holes and neutron stars, respectively, show quasi periodic oscillations (QPOs) of up to 450 and 1250 Hz. QPOs models involve the fundamental frequencies of the motion of matter in the inner, strong-field gravity-dominated disk regions. In the absence of sufficient guidance from observations, model development has so far been to a large extent phenomenological, and different interpretations are still viable. For example, competing models identify observed QPOs with the relativistic radial and vertical epicyclic motion or with relativistic nodal and periastron precession in a regime in which the relevant frequencies are drastically different from those derived from weak-field expansions of GR (see *e.g.* Stella et al. 1999).

The Fe Kα emission lines (rest energy of 6.4 - 6.7 keV) which are observed in many accreting collapsed objects, from neutron stars to supermassive black holes in Active Galactic Nuclei (AGNs), are powerful spectral diagnostics that provide a second, independent probe of the same strong gravity regions. The very broad and often markedly redshifted profiles of these lines are generated by a combination of relativistic effects in the motion of the disk plasma in the vicinity of these objects (Fabian et al. 1989). In some cases evidence has been found that the accreting black hole has non-zero angular momentum (see *e.g.* Patrick et al. 2011).

Very high-signal-to-noise LAD measurements of QPOs will discriminate between such interpretations and in the process single out GR effects in the strong field regime. These include frame dragging, relativistic precession and the presence of an innermost stable orbit. For instance LAD observations can unambiguously prove that one of QPO signal observed in stellar-mass black holes originate in the relativistic nodal precession of the innermost disk regions (see Ingram & Done 2012). LOFT will also allow direct measurements of the black hole mass and spin through timing measurements, to compare with other estimates such as mass from optical studies or spin from the thermal X-ray continuum or the Fe K-line profile. Access to dynamical timescale phenomena within their coherence time will be provided for the first time by the LAD, where so far only statistical averages of signals in the frequency domain were accessible.

As in X-ray binaries, the relativistic broad Fe-line profile that is seen in the X-ray spectrum of a number of AGNs, provides a powerful tool to investigate the accretion flow in a region where the motion is determined by strong field. LOFT will determine with very high signal to noise and accurate continuum subtraction the profile of Fe K-lines in the supermassive black holes of ~30 AGNs. Though the flux of bright AGNs is typically 100-1000 times lower than that of luminous accreting black holes in galactic binaries, their dynamical timescales (which scale with mass) are ~ 10^6 times longer, so that some 10^3 times more photons are received at the Earth per dynamical timescale. Therefore bright AGNs provide a parallel channel for investigating individual realizations of very short-term phenomena such as the motion of a single spot in the disk or the response of the Fe-line disk emissivity to flares from the illuminating source. LOFT is extremely well suited to carry out such measurements (for an example see Fig. 5). LOFT observations will provide accurate black hole masses and spins for tens of AGNs, constraining fundamental properties of supermassive black holes and of accretion flows in strong field gravity.

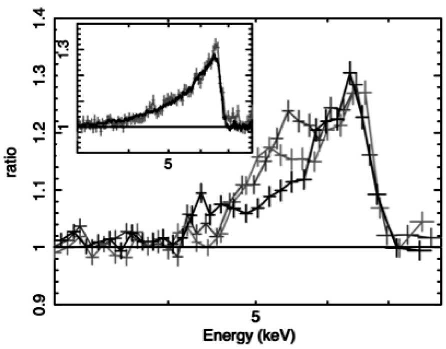

Fig. 5. Simulation of phase resolved spectroscopy of the Fe Kα line from a hot spot orbiting in the accretion disk at 4 gravitational radii $R_g = GM/c^2$, along the innermost stable circular orbit of a 2×10^7 $M_\odot$ black hole with spin $a/M = 0.5$ in a 2.5 mCrab AGN. The hot spot lasts for 4 orbits (exposure time 24 ks). Line variations (between 4 and 7 keV) due to the orbiting spot (shown here as residuals after subtraction of the integrated spectrum) over 6 different phase intervals are clearly distinguishable (only the 3 brightest intervals are shown for clarity). The insert shows the 200 ks integrated broad Fe-line profile as would be seen with the XMM/EPIC-pn and the LOFT/LAD (darker line). Fe K-line profiles probe the motion of matter very close to neutron stars and black holes

2.3. Observatory Science

While LOFT is designed for the two top level science goal outlined above, it will also be a highly flexible X-ray observatory, capable of observing thousands of X-ray sources over a variety of classes. In fact LOFT will contribute to many areas identified by ESA and international road maps such as ASTRONET and ASPERA. The LOFT Observatory Science Matrix in Table 1 summarizes the observations and LOFT instruments that can contribute much progress in these areas. The LAD's throughput and capabilities will rep-

Table 1. LOFT Observatory Science Matrix (sources allowing studies of the main Observatory Science categories with the LAD and/or the WFM are indicated)

Observatory Science Sources	Accretion-Ejection	Strong B-fields	Cosmic Explosions	Cosmological Objects	Transient Phenomena
Cataclysmic Variables	LAD, WFM	LAD	LAD, WFM		LAD, WFM
Low Mass XRBs	LAD, WFM	LAD, WFM			LAD, WFM
Type I X-ray Bursters	LAD, WFM		LAD, WFM		LAD, WFM
High Mass XRBs	LAD, WFM	LAD, WFM	LAD, WFM		LAD, WFM
Isolated Neutron Stars		LAD			LAD
Magnetars		LAD, WFM	LAD, WFM		LAD, WFM
Flare Stars		LAD			LAD, WFM
Nearby Galaxies	LAD, WFM	LAD, WFM	LAD		LAD
Tidal Disruptions	LAD, WFM				LAD, WFM
Bright AGNs	LAD, WFM				LAD, WFM
Gamma-ray Bursts	WFM		WFM	WFM	WFM
CXB Fluctuations				LAD	

resent a dramatic improvement to the state of the art and enable the community at large to address key questions in high energy astrophysics. Through pointed observations with the LAD, LOFT is also the natural X-ray partner of other large-scale facilities across the messenger spectrum that will be available in the 2020s, such as the SKA and its pathfinders, the LSST, the ELTs, or the CTA, as well as ground- and space-based gravitational wave interferometers and neutrino telescopes. The large field of view, high sensitivity, and good spectral resolution of the LOFT WFM make the satellite a discovery machine for the variable and transient sky, and for picking up new transient sources for follow-up with the LAD and other facilities. Phenomena that will be monitored with LOFT in multiwavelength campaigns range from star flares, via the spectral variability of magnetized white dwarfs and neutron stars, and black holes to Blazar outbursts and tidal disruption events associated with supermassive black holes in AGNs.

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