

The Advanced X-ray Timing Array (AXTAR): A US MIDE X Mission Concept

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AXTAR is a NASA MIDE X mission concept 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. It is optimized for submillisecond timing of bright Galactic X-ray sources in order to study phenomena at the natural time scales of neutron star surfaces and black hole event horizons, thus probing the physics of ultradense matter, strongly curved spacetimes, and intense magnetic fields. AXTAR's main instrument is a collimated, thick Si pixel detector with 2–50 keV coverage and over 3 square meters effective area. For timing observations of accreting neutron stars and black holes, AXTAR provides at least a factor of five improvement in sensitivity over the RXTE PCA. AXTAR also carries a sensitive sky monitor that acts as a trigger for pointed observations of X-ray transients in addition to providing high duty cycle monitoring of the X-ray sky. We review the science goals and design choices that face a next generation timing mission. We then describe the technical concept for AXTAR and summarize a preliminary mission design study at the NASA/MSFC Advanced Concepts Office.

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1. Introduction

The properties of ultradense matter and strongly curved spacetime and the behavior of matter in the extreme environments near compact objects are among the most fundamental problems in astrophysics. X-ray timing measurements have powerful advantages for studying these problems [1]. The X-ray band contains most of the power emitted by accreting neutron stars and black holes, and this radiation is relatively penetrating even in these complex environments. The millisecond X-ray variability of these objects encodes their basic physical parameters, and interpretation of this variability is relatively straightforward for rotating or orbital origins. In many cases, the properties of the X-ray variability allow extremely precise measurements and detailed quantitative inferences.

The scientific promise of X-ray timing has been spectacularly demonstrated by the success of NASA's Rossi X-ray Timing Explorer (RXTE; effective area $A_{\text{eff}} = 0.6 \text{ m}^2$; launched 1995), which has revealed an extraordinary range of previously unknown variability phenomena from neutron stars and black holes. However, redeeming that promise to exploit these phenomena as tools for answering fundamental astrophysical questions will require a more sensitive follow-on mission. A detailed scientific case for such a mission was first explored at the conference *X-Ray Timing 2003; Rossi and Beyond* in Cambridge, MA, USA [2], and has been discussed in more detail at this 2010 meeting in Champéry, Switzerland. Many of the issues concerning the fundamental properties of neutron stars and black holes have been identified as high priority scientific questions by the 2010 U.S. Decadal Survey of Astronomy and Astrophysics [3].

In this paper we describe the Advanced X-ray Timing Array (AXTAR), a new mission concept with significantly larger effective area than RXTE. AXTAR was originally proposed as an $\sim 8 \text{ m}^2$ medium-class probe concept in the 2007 NASA Astrophysics Strategic Mission Concept Study call [4]. More recently, we have been developing as a $\sim 4 \text{ m}^2$ Medium Explorer (MIDEX) class mission concept [5].

2. Design Choices

The first, critical design decision for any future X-ray timing mission is whether to include a focusing optic or to adopt a collimated detector as was done with RXTE. Each architecture has advantages and disadvantages and is particularly well matched to particular science questions.

Focusing optics. The primary benefit of a focusing optic is that the X-rays from the source of interest are focused onto a small detector region. This allows a large reduction in the background counting rate and enables studies of faint sources (e.g., rotation-powered pulsars, AGN, iron line sources, etc.). In addition, the small detector area can reduce the required power and make it easier to achieve very good (e.g. $< 200 \text{ eV}$) energy resolution. The drawbacks of focusing systems include the fact that it is difficult to achieve good efficiency for higher energy X-rays, since mirror systems become particularly challenging above 10 keV. Such coverage can be critical to many science topics in X-ray timing, particularly with respect to X-ray binaries. To get significant effective area at high energies, one is driven to designs with small grazing angles and long focal lengths. As a result, many focusing X-ray telescopes have large masses, which increases cost, and large moments of inertia, which makes flexible scheduling and rapid repointing difficult. An additional

challenge with focusing optics is that the concentration of flux onto a small detector area can lead to significant deadtime effects, limiting the ability to observe bright targets.

One can also choose the focusing approach for opportunistic or serendipitous reasons, such as the community plans for the flagship focusing X-ray astronomy mission IXO¹. The HTRS [6] instrument (a major topic of this conference) would add powerful high-count-rate timing capabilities to IXO/ATHENA. It provides 1–2 m² collecting area over the band 0.3 to 10 keV, μ s time resolution and minimal deadtime on bright sources, mitigating one of the above drawbacks. However, since X-ray timing was not a primary requirements driver for this mission, some of the other drawbacks (hard X-ray response, rapid repointing) remain. Another approach to mitigating some drawbacks is taken by the proposed NICER experiment [7], which adopts single-bounce X-ray concentrators instead of multi-mirror true imaging systems. This provides good background rejection with increased area efficiency and reduced mass. In addition, they use an array of many small optics, which enables them to use a short focal length of only 1.5 meters for a more compact, agile design.

Collimated detectors. The alternative technical approach, a collimated design, has a different set of strengths and weaknesses. Previous timing missions (e.g. SAS-3, EXOSAT, Ginga, RXTE, and the forthcoming Indian ASTROSAT) employed collimated proportional counters, but these are too heavy for significantly larger effective areas. However, one can instead substitute silicon detectors and achieve a substantial reduction in mass. In that case, the main strength of collimation is that, for the same cost and mass, one can achieve significantly larger effective areas than with focusing. Also, a collimated design requires no optics, designs can much more easily accommodate high energies. Moreover, without long optical benches, the moment of inertia can be small, allowing rapid repointing. Since the source photons are not concentrated on the detectors, achieving low deadtime on bright sources is straightforward.

The primary drawback of collimated designs is that the lack of focusing means that the instrumental and diffuse X-ray background rates will be considerably higher. For bright sources, this is not a problem, but faint source observations, particularly those that depend on accurate knowledge of the background rate, will be impaired. In addition, the need to instrument a very large area of detectors implies that the power available for the detector readout will be limited. This makes achieving very good energy resolution more difficult and power can become a limiting factor.

Science requirements. Ultimately, the choice of focusing versus collimation is driven by one's science requirements. Our primary scientific objectives require observations of accreting neutron stars and black holes in Galactic X-ray binaries. These are bright sources which can also have intense X-ray flares or bursts, leading to high count rates. Many of the interesting timing phenomena discovered by RXTE are strongest in the hard X-ray band, requiring sensitivity above 10 keV. Finally, many of these sources transition between different accretion/spectral states, and some key timing phenomena are preferentially present in a particular state; thus, flexible scheduling and rapid repointing ability are required. These considerations lead us to a collimated design for the AXTAR concept presented below. The proposed LOFT mission [8], which is driven by many of the same considerations, has also adopted a collimated approach.

¹Now renamed ATHENA and under redesign as of early 2011

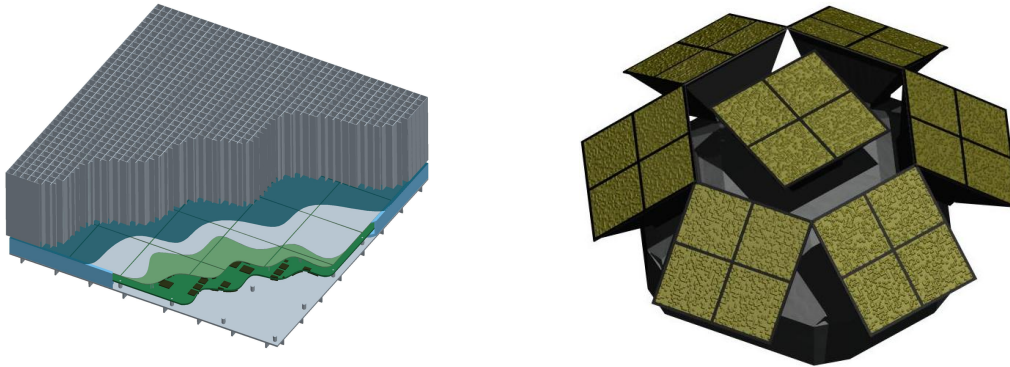


Figure 1: Left: Cutaway rendering of a LATA supermodule consisting of a 5×5 array of 10×10 cm detectors. The components from top to bottom are the collimator, light shield, silicon detectors, interposer board, and digital board, mounted in a box that provides support and shielding. Note that the collimator cell size is not to scale. **Right:** A cluster of 7 SM cameras.

3. Instrument Description

AXTAR hosts two science instruments, the Large Area Timing Array (LATA), and the Sky Monitor (SM). Both are based on large-area (10×10 cm) 2-mm thick silicon pixel detectors, which have been developed at NRL. The thick detectors enable good efficiency up to at least 50 keV. The detectors are divided into 2.5×2.5 mm pixels. On the LATA, the pixilation keeps the capacitance low, enabling 600 eV energy resolution with a low power readout ASIC, as well as ensuring that dead time is not an issue. For the SM, the 2-D position resolution of the detectors is exploited to form the basis for a 2-D wide-field coded aperture mask camera with a $40^\circ \times 40^\circ$ field of view. High duty-cycle coverage of a large fraction of the sky is achieved by mounting several of these cameras on the spacecraft.

The overall performance parameters are shown in Table 1 and the instruments are described in more detail in [5].

4. Mission Concept Study

In this section, we briefly summarize the baseline design resulting from a mission concept study at the MSFC Advanced Concepts Office. For purposes of this study, we hypothesize a 2014 call for proposals for a \sim \\$300M (excluding launch) MIDEX class mission to be launched in 2019. Full details of the study input parameters and results are described in [5].

The optimal orbit was determined to be 585 km altitude circular orbit with as low an inclination as possible. Given an initial mass estimate of 2000 kg, two launch vehicle candidates were selected: the Orbital Sciences Corporation's Taurus II and the SpaceX Falcon 9. The size of the Taurus II determined the spacecraft configuration and limited the science instruments to 20 LATA supermodules and 27 sky monitor cameras, for a total gross mass (dry mass, inert mass, and propellant) of 2650 kg (including 30% contingency) and a total power budget of 1583W (including spacecraft systems, science instruments, and a 30% growth margin). Spacecraft structures

Table 1: Mission Requirements

Parameter	Baseline	Drivers	Technology Factors
<i>Large Area Timing Array (LATA)</i>			
Effective Area	3.2 m ²	NS radius, BH QPOs	Mass, cost, power
Minimum Energy	1.8 keV	Source states, absorption meas., soft srcs	Detector electronics noise
Maximum Energy	>30 keV	BH QPOs, NS kHz QPOs, Cycl. lines	Silicon thickness
Deadtime	10% @ 10 Crab*	Bright sources, X-ray bursts	Digital elec. design, pixel size
Time Resolution	1 μ s	Resolve ms oscillations	Shaping time, GPS, Digital elec.
<i>Sky Monitor (SM)</i>			
Sensitivity (1 d)	< 5 mCrab*	Faint transients, multi-source monitoring	Camera size/weight/power
Sky Coverage	> 2 sr	TOO triggering, multi-source monitoring	# cameras vs. gimbaled designs
Source Location	1 arcmin	Transient followup	Pixel size, camera dimensions
<i>AXTAR Mission</i>			
Solar Avoidance Ang	30°	Access to transients	Thermal/Power design
Telemetry Rate	1 Mbps	Bright sources	Ground stations/TDRSS costs
Slew Rate	> 6° min ⁻¹	Flexible scheduling, fast TOO response	Reaction wheels

*1 Crab = 3.2×10^{-8} erg cm⁻² s⁻¹ (2–30 keV)

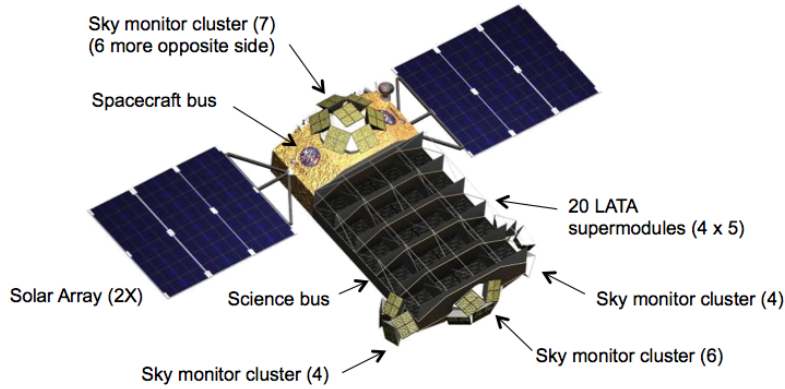


Figure 2: AXTAR spacecraft configuration with 20 LATA supermodules. This configuration is within the volume and payload mass limits for a Taurus II launcher, and will also easily work with a Falcon 9 launcher.

consisted of 2020-T351 aluminum panels, struts, and frames for component mounting which also double as radiators for thermal management. Cosmic and solar radiation shielding is included in the spacecraft structural mass. The communications system consists of an S-band transmitter for spacecraft telemetry and communications and an X-band transmitter for science data downloads, using two ground stations (Southpoint Hawaii and Kourou Guiana), allowing expected continuous data rates from the LATA and Sky Monitor with headroom for over 6 LATA observations per day of very bright (several Crab) sources.

The avionics system consists of Proton 200 flight computers (TRL 6) and Surrey data recorders (TRL 8). Attitude knowledge is provided by TRL 8 star trackers and IMUs. AXTAR's modest slewing and pointing requirements, 180 deg in 30 minutes and < 5 arcmin, respectively, allow use of off-the-shelf reaction wheels with magnetic torque rods for contingency and angular momentum

dumping. Inertial pointings of up to 28 hours are allowed. Thermal control is achieved using passive components including multilayer insulation, high emissivity paint, coatings, and heaters, to maintain acceptable temperature ranges. To allow the spacecraft to be de-orbited at the end of the mission, a propulsion system was included. The mission concept study found that AXTAR was straightforward from an engineering point of view, requiring no new technologies to implement the mission.

5. Current Status and Plans

The AXTAR concept continues to be studied in preparation for the next NASA MIDEX Announcement of Opportunity, which could come as early as 2014. We are pursuing several lines of technical development as well as studying design alternatives.

Our concept study made clear that a large collimator, such as the one used on the RXTE PCA, becomes the dominant mass driver for the instrument when the heavy gas containment vessels are replaced by lightweight solid state detectors as planned for AXTAR. Therefore, there is a major mass savings to be had by looking at alternatives. One option is lead-glass micro-capillary plate collimators, as currently planned for the LOFT mission. These can be thin and light, but their performance is poor at high energies (30 keV and above) and achieving a high open fraction ($> 70\%$ is challenging). We are developing 2-mm thick micromachined tantalum collimators that could provide excellent high energy performance with a significant mass reduction that would reduce the expected cost of the AXTAR mission.

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