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**MonSTER: The Monitoring Spectroscopic Telescope for Energetic Radiation**

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**ABSTRACT**

The *Monitoring Spectroscopic Telescope for Energetic Radiation (MonSTER)* will provide time-resolved, broadband X-ray spectroscopy (3-50 keV) of stellar mass X-ray Binary systems (XRBs) as they undergo outburst. *MonSTER* will be dedicated to following these sources for weeks or months at a time, with instrumentation optimized for sensitivity and spectral resolution across the crucial iron line complex that will provide a complete picture of the dynamics of key parameters such as the disk inner radius, the ionization state, and the temperature and optical depth of the corona as the outburst evolves. With flight heritage of the X-ray detectors and collimator design and modest requirements on the spacecraft bus pointing, *MonSTER* provides an inexpensive alternative to dedicating time from flagship missions to study accretion in extreme environments.

**INTRODUCTION**

Since the dawn of X-ray astronomy, observations have revealed the dynamic nature of the X-ray sky. The population of transient galactic X-ray sources is dominated by compact objects (black holes and neutron stars) accreting from a companion main sequence star either through Roche lobe overflow or via the stellar wind from the companion. The inflowing material forms an accretion disk around the compact object with temperatures hot enough to produce copious amounts of thermal X-rays and giving rise to a “corona” of non-thermal electrons emitting in the hard X-ray band. Compact objects in our galaxy provide an excellent laboratory in which to study matter in extreme conditions. Coverage over the hard X-ray ( $E > 2$  keV) is essential to study many of the high energy accretion processes at work in these systems.

The *Monitoring Spectroscopic Telescope for Energetic Radiation (MonSTER)* is a NASA Small Satellite concept designed to provide time-resolved, broadband hard X-ray spectroscopy (from  $\sim 2$  keV to at least 30 keV) of stellar mass X-ray Binary systems (XRBs) as they undergo outburst. The *MonSTER* instrument is composed of compact collimators backed by an array of advanced solid-state detectors, providing a small ( $\sim 1$  deg) field-of-view instrument optimized with moderate energy resolution (0.4 keV at 6 keV).

*MonSTER* is designed to follow the brightest sources in the X-ray sky for weeks or months at a time and is optimized for sensitivity and spectral resolution across the crucial iron line complex. The spectrum in this region contains observables related to the accretion disk

(including the disk inner radius, the ionization state of the disk) as well as the enigmatic corona, which produces the hard X-ray ( $E > 10$  keV) emission and illuminates the accretion disk, resulting in the so-called “Compton reflection” emission. While dedicated observations with *XMM-Newton*, *Chandra*, and *NuSTAR* have provide snapshots of these systems, these systems are highly dynamic and change unpredictably. *MonSTER* will provide a unique set of contiguous observations of several X-ray binary systems per year as they go through their outbursting cycle, filling a crucial hole in our understanding of the accretion mechanisms around compact objects.

While traditional CubeSat platforms have relied on commercial off-the-shelf (COTS) parts, in the 2020s we expect to use CubeSat / SmallSats as full-featured observational platforms. This includes moving beyond off-the-shelf detector components to build-to-print “custom” parts that utilize design and development efforts from larger mission. *MonSTER* is designed primarily with high technology readiness level (TRL) components in mind, with some flexibility to also serve as a test bed for future mission technologies.

In the subsequent sections of this paper we discuss the science for the *MonSTER* mission concept, the baseline mission design, the state of the instrument technology, and the enabling SmallSat technological advances that make *MonSTER* a compelling scientific platform.

## SCIENCE BACKGROUND

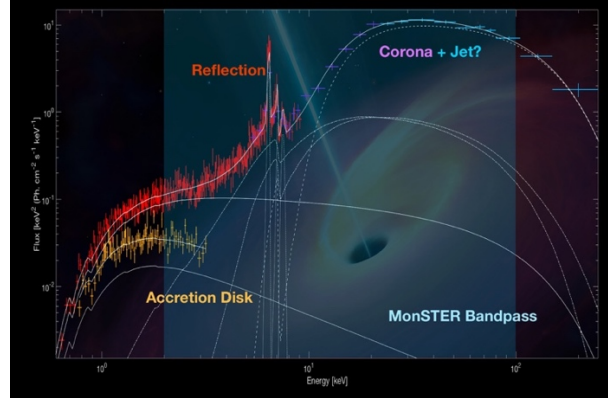
### *X-ray Transients*

Black holes are of utmost importance in physics for they represent the ultimate test of general relativity. In astrophysics, stellar-mass black holes are the endpoints of stellar evolution, while supermassive black holes in active galactic nuclei (AGN) are chief agents in determining the structure of the universe via “feedback”<sup>1</sup>. Black hole binaries (BHBs) and supermassive black holes in AGN share several observational properties derived from the connection with their surroundings: e.g.; powerful relativistic jets<sup>2</sup>, quasi-periodic oscillations (QPOs)<sup>3</sup>, relativistically-broadened Fe lines<sup>4</sup>, X-ray reverberation<sup>5</sup>, and more. The scale-free connection between BHBs and AGN exemplified by the “fundamental plane of black hole activity”<sup>6</sup>, implies that one can simultaneously explore the physics of both BHBs and AGNs.

Importantly, most of our current knowledge of the properties and behavior of BHBs has been acquired through closely monitoring their X-ray emissions every time one of these sources goes into outburst. The premier database for the synoptic study of the brightest black holes is that amassed by the *RXTE*<sup>7</sup>. During its 1996–2012 mission, the PCA and HEXTE detectors aboard *RXTE* obtained 15,000 spectra of 29 black hole binaries with typical exposure times of a few kiloseconds per spectrum. Each one of these black holes were observed several hundred times on a near-daily basis. During outbursts, these sources experience the full range of accreting black hole behavior, transitioning between states as their luminosities ramp up to the Eddington limit and then decay. Over the course of an outburst, they alternately produce steady and ballistic jets, quasi periodic oscillations (QPOs), and spectra that extend up to several MeV<sup>3</sup>.

Most of the phenomena observed at high-energies are produced in the inner region of the black hole’s accretion disk where gas orbits at relativistic speeds. Reminiscent of the Sun, the X-ray source is comprised of a  $\sim 10^6$  K accretion-disk photosphere, which is veiled by  $\sim 10^9$  K coronal gas. The corona illuminates the cold disk producing a rich atomic “reflection” spectrum, whose features are blurred and distorted by gravitational redshift and Doppler effects (Figure 1). The dominant features of a reflection spectrum are the Fe K emission ( $\sim 6.4$ - $6.9$  keV), the absorption K-edge ( $\sim 7$ - $8$  keV), and the “Compton hump” ( $\sim 20$ - $30$  keV).

Accreting BHBs are highly variable, with most only seen during outbursts when instabilities in their accretion disks drive mass accretion onto the compact object. The emission during these periods shows



**Figure 1. Spectral coverage for *MonSTER*, along with the fiducial spectral energy distribution for a black hole system across the X-ray band. *MonSTER* extends from roughly 2 keV and will cover at least up to the Compton peak at 30 keV and, depending on the shape of the underlying spectrum and the brightness of the source, to much higher energies.**

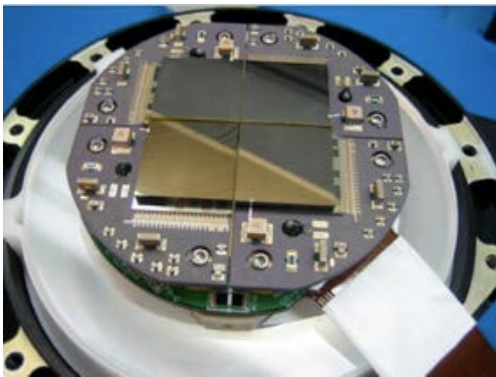
evidence for multiple canonical accretion “states” characterized by having a spectrum dominated by the accretion disk or by the corona<sup>3</sup>. While the outburst itself and the various types of accretion states are thought to be related to accretion instabilities, the transition between various states is unpredictable and has rarely (if ever) been directly observed.

Since the *Rossi X-ray Timing Explorer (RXTE)* ceased operation, there has not been an instrument with sufficient spectral resolution and sensitivity to provide such uninterrupted coverage of these systems. Current observations are obtained either by low spectral-resolution monitoring mission, or are time limited, due to the oversubscribed of the observatory. We lack a modern instrument with the capabilities to provide, dedicated broad-band coverage of X-ray binaries throughout their outburst, addressing a major gap in the observation record of these sources.

### *Multi-wavelength Science*

One key aspect to the study of black hole systems over the last decade has been the rise of multi-wavelength (radio, optical, X-ray, gamma-ray, and VHE) observations of X-ray sources. A major development since *RXTE* has been the availability of high-speed, ground-based optical cameras. This has already been shown to be a powerful multi-wavelength tool for following the brightest XRB flares<sup>8</sup>. However, advancement in this space has been limited by the necessity of coordinating many large, heavily oversubscribed observatories.

The standard operational approach for scheduling a major observatory (such as *Chandra*, and *XMM-Newton*, or *NuSTAR*) relies on observation plans solicited from the astronomical community (typically once per year). Proposals are ranked by a time allocation committee (TAC) and then recommended to the observatory for observation. Observatories typically respond to transient events via “Target of Opportunity” (ToO) observations, where observational schedule is interrupted so that the telescope can slew over to the transient source. Because the X-ray emission from many sources is relatively weak, typical observations are long (lasting days or weeks at a time). Interrupting the observing schedule is both disruptive and costly. Managing to interrupt the observing schedule for several major observatories and attempt to simultaneously observe a single X-ray target can be prohibitively expensive both in operational cost and in the opportunity cost to the observatories.



**Figure 2.** One of the two flight focal plane arrays for *NuSTAR* showing the 2x2 “pie wedge” configuration of the *NuSTAR* CdZnTe detectors.

### SCIENCE INSTRUMENTS

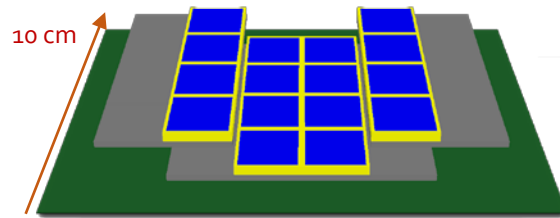
*MonSTER* will be an instrument dedicated to the X-ray broadband (2-50 keV) monitoring of X-ray transients. The goal is to take advantage of the cost savings made possible by using a CubeSat platform to provide unique scientific data that is otherwise too expensive to obtain with major observatories. The mission will be dedicated to long-term, high cadence, high spectral resolution monitoring of X-ray sources using a classic “collimated telescope” approach.

*MonSTER* leverages other missions to provide transient localizations (such as transient alerts from the *Burst Alert Telescope (BAT)* on the *Gehrels Swift Observatory*) to identify the source location. And, because *MonSTER* is designed to look at the brightest source in the sky, this allows us to optimize the instrument design for observing a single, bright, hard X-ray source.

### Detectors

The focal plane for *MonSTER* will consist of high flight heritage instruments from *NuSTAR*. These CdZnTe detectors (Figure 2) have already demonstrated excellent energy resolution (400 eV FWHM at 6 keV). The observations with *NuSTAR* have led to a watershed moment in the study of black hole binaries<sup>9-13</sup> and would be an ideal match to the *MonSTER* instrument design.

While flying flight-proven detectors reduces the overall mission risk, we are also considering flying new detectors that are currently under development. These detectors are also based on a CdTe / CdZnTe X-ray sensor mated to a custom Application Specific Integrated Circuit (ASIC) developed under NASA APRA funding at Caltech. These prototype detectors are current at TRL 4 and will be advanced to TRL 5 over the next 18 months and are in development to support the *High Energy X-ray Probe (HEX-P)* a NASA Probe class (~\$1B) mission concept<sup>14</sup>. *MonSTER* provides an excellent test bed for these detectors to rapidly advance them to TRL 9 in the early 2020s.



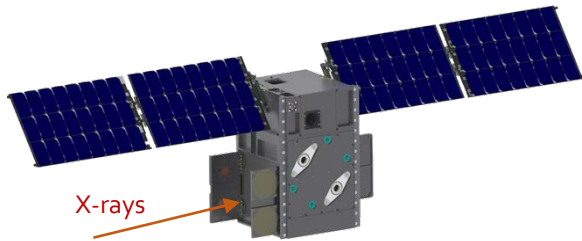
**Figure 2.** A conceptual layout showing the focal plane design for *HEX-P* (citation here). Each of the CdZnTe detectors (blue) is the same size as the *NuSTAR* detectors shown in Figure 1. This 4x4 array results in 4x the detector area compared with the *NuSTAR* design but still fits within a 1U volume.

### Collimators

The main goal for the X-ray collimators is to limit the field-of-view (FoV) of the X-ray detectors so that *MonSTER* can target individual X-ray point sources. The FoV of the collimator is defined by the depth of the collimator well (i.e. the thickness of the collimator) and the size of the collimator elements (here, the diameter of the collimator holes). Since X-rays are penetrating radiation, the collimator has to be constructed of relatively high Z (high atomic number) material so that

the collimator is opaque to X-rays across the desired bandpass.

For *MonSTER* we baseline an X-ray collimated developed at the Naval Research Lab (NRL) as a prototype for the *STOBE-X* NASA Probe class mission concept. This collimator is constructed out of blocks of Ta, with the collimator holes micro-machined using a laser drill and then chemically etched for smoothness<sup>15</sup>. This technique produces collimator holes on the order of 57  $\mu\text{m}$  on a pitch (the distance between collimator holes) of 60  $\mu\text{m}$  with an open fraction of 70%. For collimator thicknesses of a few mm, this produces a FoV of  $\sim 1^\circ$  on the sky, which is sufficient for *MonSTER* as it will always be targeting the brightest X-ray sources on the sky and we do not anticipate significant source confusion.



**Figure 3. A 12U Blue Canyon Technology XB12 spacecraft. The “large form factor” *MonSTER* detectors are assumed to occupy roughly a 4U (2x2U) volume, with the remainder dedicated to readout electronics, avionics, and communications.**

### *Instrument Requirements and Baseline*

The standard units for X-ray astronomy are given in “Crab” units over a given bandpass, based on the X-ray spectrum of the Crab nebula (the standard calibration source for X-ray astronomy). We want to be able to perform detailed spectral measurements of an X-ray source that produces 100 mCrab in the *Monitor All-Sky Image (MAXI)*<sup>16</sup> instrument over the 4-10 keV bandpass. This both guarantees that over the nominal 1-year mission lifetime we should observe at least one X-ray transient in outburst and allows us to study persistently bright X-ray sources.

To accomplish this, we are considering three form factors for the *MonSTER* instrumentation: a 1U *NuSTAR*-like focal plane array producing 16  $\text{cm}^2$  of detector area, a 1U *HEX-P*-like focal plane array producing 64  $\text{cm}^2$  of detector area, and large form factor with a volume of 4U consistent of four individual 1U *HEX-P*-like modules producing 246  $\text{cm}^2$  of detector area. We’ve performed simulations of a BHB source using all three of these assumptions and can clearly

detect the sources up to 50 keV even in the smallest form factor within a 50 ks observation (roughly one observation per day). The larger form factors enable shorter time-scale variability studies and improved statistical power across the Fe line region, enhancing the scientific return.

For much of our science, we want to bring every photon down to the ground so that we can perform timing analyses to search for periodic and aperiodic signals. This will be primarily limited by the observed count rate of the events, which scales roughly with the focal plane size. We anticipate the limiting factor to be the ability of the *MonSTER* spacecraft bus to downlink the data, so we leave the precise choice of both form factor and spacecraft bus an open question to be addressed in a future JPL Team Xc study.

As a first estimate, we can look at the data rates for a 1U *NuSTAR*-like focal plane. For a source with a typical hard X-ray spectrum and a flux of 100 mCrab in the *MAXI* band, the source produces roughly 20 counts per second in the *MonSTER* detectors. If we scale this up to a the full 4U *HEX-P*-style instrument, we anticipate wanting to handle data rates in excess of at least 400 counts per second. Based on the *NuSTAR* telemetry format and an observing efficiency of 55% (account for the time spent when the source is not visible due to occultation by the Earth), this results in roughly 1.2 GB per day of accumulated data. Even assuming a data compression factor of 4, this still requires nearly 400 MB per day of downlink to prevent data loss. A detailed study of the capabilities and possibilities for the *MonSTER* communications architecture utilizing X-band, Ka-band, and/or optical communications will be performed in the near future.

### *Attitude Control, Accuracy, and Knowledge*

One key aspect here is the ability of the spacecraft to place the source “on-axis” so that the X-ray source is centered on FoV of the X-ray collimators. We require that the pointing jitter (the relative motion of the X-ray source to the collimator FoV) be either small enough that we can ignore the changing instrument response or well-measured enough that we can accurately account for the changing attitude in post processing. The relatively large FoV of the X-ray collimators at  $\sim 1$  degree implies that the current generation of ACS systems flying on instruments such as *MinXSS*<sup>17</sup> has already demonstrated that the pointing requirements can be achieved.

### **SUMMARY**

*MonSTER* is a low-cost instrument using advanced, high TRL and advanced instrumentation to provide observational data that both fills in a gap in our

knowledge of X-ray binaries and provides a unique opportunity for broad, multi-wavelength studies of these systems.

*MonSTER* is achievable with only moderate technological advances required on the CubeSat platform, predominantly related to the adoption of high speed communications of the CubeSat to the ground.

Future studies of the *MonSTER* mission concept will optimize the instrument design both for scientific return and to accommodate the current state-of-the-art of CubeSat technology.

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