Uncovering High-Energy Transient Phenomena with Coded Aperture Imaging

Background and Motivation: In time-domain astrophysics, the detection of high-energy transients is limited to a small number of instruments (Fermi, MAX, BAT, etc.). The *Swift* Burst Alert System (BAT) covers 1.4 Steradians, missing ~90% of high-energy transient phenomena from X-ray binaries, stellar flares, supernovae, and Active Galactic Nuclei. X-ray binaries are a black hole (BH) or neutron star (NS) with a bound stellar companion donating mass. Short (~seconds) Gamma-ray bursts (GRBs) from binaries allow the study of BH formation and gravitational waves detected through NS-NS and NS-BH mergers. Long (~minutes) GRBs further the study of the most luminous electromagnetic bursts known (>10^3 times more than supernovae) and massive star formation vs. redshift providing a chance to measure the epoch of formation of the very first massive stars (Pop III) [1]. For these reasons, the creation of **a time-domain astrophysics program in transient detection is a top priority in the Astro 2020 Decadal Survey** [2]. As my contribution to my ongoing collaboration with the Harvard–Smithsonian Center for Astrophysics (CfA), **I propose to develop the embedded image processing system and hardware peripherals for the High-resolution SmallSAT Extremes Explorers (HSEE) telescopes, enabling real-time on-board detection, characterization, and announcement of transient X-ray sources.** The HSEE wide-field (~50 deg. × 50 deg.) X-ray telescopes, sensitive between 3 keV - 3 MeV, offer **100× broader** energy coverage than *Swift*/BAT (15 - 150 keV). A fully realized HSEE mission will consist of two telescopes in low Earth orbit (LEO) on opposite sides of the Earth. This ensures that no sources are blocked by the Earth (removing an up to 45-minute orbiting delay) enabling continuous observations which is not possible with current instruments. This mission will be proposed for a NASA Small Explorer Mission (SMEX) to enable enhanced observation and characterization of high-energy astrophysics transients.

Research Project: Cadmium Zinc Telluride (CZT) detectors enable greatly enhanced detection efficiency at higher energies and thicknesses than is possible with Si detectors [4]. The HSEE detector plane will be composed of a 16 × 16 array of such detectors mounted within a coded aperture telescope. The coded mask for HSEE is a grid pattern of precision etched holes in a Tungsten sheet fixed 80 cm above the detector plane. For any given source, the shadow cast by the coded mask on the detector plane spatially encodes the source position. The sky image is reconstructed using cross-correlation of the detector plane count map and mask pattern. Current coded mask aperture models show a lower coded percentage than *Swift/*BAT's half coded mask reduces background counts, yielding increased sensitivity [3]. Outside the FOV (background events), Pb/Sn/Cu shielding will attenuate a predicted ≥90% of counts ≤300 keV.

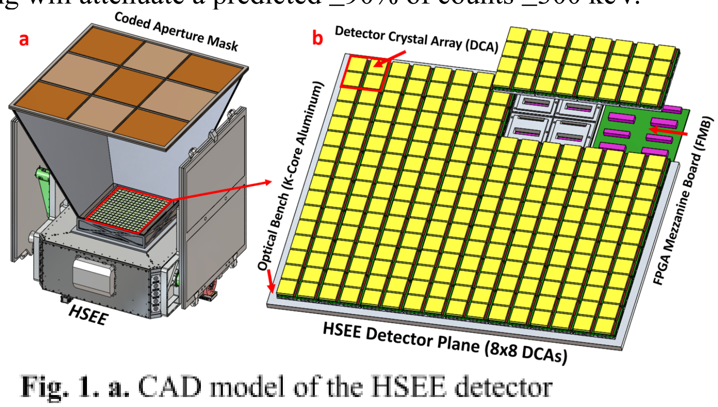

Fig. 1. a. CAD model of the HSEE detector **b.** Exploded model of HSEE detector plane showing 256 DCAs on 64 FPGA mezzanine boards (Violette)

Each CZT detector is read out by a NuASIC, an application-specific integrated circuit developed for the NuSTAR mission. To capture signals before and after the trigger, a continuous ring buffer will store data to be transmitted once triggered for each of the 32 × 32 pixels in the NuASIC. Each NuASIC pixel independently processes signals with two amplifier stages and a discriminator to compare signals up to ~300 keV against the 3 keV energy threshold. During a post-trigger delay, the event and baseline current samples are transmitted off each NuASIC detector for every pixel. The baseline sample can be subtracted from the event sample to determine the event energy. To offset leakage current, the NuASIC supports a charge pump mode (CPM). This compensates the preamplifier output to cancel the standing current through the amplifier, yielding an improved spectral resolution and possibly lower energy threshold at the cost of additional dead time [5]. As part of this project, I will help lead the development of a second detector consisting of four ~8 cm × ~8 cm, ~1.5 cm thick LaBr crystals that will extend HSEE's energy range and FOV. The phases of this project are outlined as follows: **(1)** In year one, I will optimize the NuASIC amplifier and reference parameters to stabilize CPM operation. My experiences working with amplifiers in courses, teaching, and research will expedite this process for >800 NuASIC detectors. The calibrated detectors will be graded with the best 512 NuASIC detectors selected for integration into the HSEE detector planes. I will use a low-energy fluorescence line X-ray source to characterize detector performance and constrain the expected ~3 KeV low-energy threshold. Testing will be conducted in a thermal vacuum at CfA with a beryllium X-ray transmission window which remains opaque to ambient light while allowing for X-ray sources to test flood-illumination [5]. **(2)** In year two, I will use my transient detection pipeline experience to create an embedded pipeline for the energy band, FOV, and angular resolution of HSEE to characterize sources and record their spectra and count rate. Embedded software must also report sources to the Gamma-ray Coordinates Network to rapidly release the source position and fluxes. This work is possible in one year by adapting existing software and tools developed by the CfA and our collaborators. **(3)** In years three and four, I will integrate image processing and source identification onboard HSEE. My largest task will be designing the ring buffer electronics and adapting its field-programmable gate array (FPGA) readout for the embedded pipeline. I previously ran Verilog FPGA test benches in an elective course, designing circuitry for data processing, converting processed data to AC signals, and sending these signals via Bluetooth to receivers, which will be vital to this step. My experience with graphical acceleration will be employed for a low-power mode NVIDIA GPU farm for image processing. To widen the energy band to ~3 MeV and confirm long vs. short GRBs, I will determine the optimal positioning and number of Silicon Photomultipliers (SiPMs) to uniformly collect light over a LaBr crystal. This will use my skills configuring SiPM arrays from a previous small elective project where I estimated the percentage of cosmic rays entering my apartment with an incident angle $\leq 1°$. **(4)** In year five, I will build a larger thermal vacuum to test the HSEE detector plane and calibrate and characterize an engineering model of the integrated HSEE detector and SiPM array in a spacelike environment. To prepare for this phase, I studied statistical methods such as principal component analysis and Markov chain Monte Carlo in a graduate-level course this spring.

Intellectual Merit: We will create a 2024 SMEX proposal for HSEE that would see its launch in 2029, which is consistent with my expected time for graduate study at Harvard. The experience of the CfA on previous NASA missions and the experience of Professor Grindlay's group with CZT coded aperture telescopes launched in high-altitude balloons [5] will strengthen this proposal. Regardless of the outcome of the SMEX proposal, the CfA is the ideal place for me to conduct this research due to their familiarity with CZT coded aperture telescopes [5] and the ongoing APRA fund that ensures **development is not contingent on winning a proposal.** At the conclusion of my time at the CfA, we will have an engineering model of the most capable X-ray telescope of its class, **creating a pathway for the discovery and understanding of high-energy transients.**

Broader Impact: Only two dozen (dynamically confirmed) X-ray binaries with stellar mass black holes have been discovered to date [7] making estimating their population and understanding how these BH + K dwarf star binaries form not currently feasible. While all current discoveries occurred during extremely luminous outbursts that occur on time scales of 10 - 50 years, HSEE will open a pathway for discovering these systems in their deep quiescent state (99.5% of the time, when not undergoing an outburst). HSEE's higher resolution and broad-band (3 - 300 keV) will enhance recently discovered (with BAT) detections in more common short-duration (~2 - 5 days) flares. In addition, GRB detections advance our understanding of black hole and neutron star mergers that produce gravitational wave outbursts and the formation of massive stars that collapse to form stellar mass black holes. Combining HSEE with current and future high energy transient instruments offers the sensitivity and full-sky coverage to discover GRBs from the collapse of the first PopIII stars that formed before the first galaxies in the Early Universe. To the general public, black holes and supernovae have enormous power to fascinate. Participating in monthly public CfA Observing Nights attended by Boston area families will allow me to engage the public with the enthralling stories of black hole hunting. By supplementing my Citizen Schools curricula with these stories, I hope to spark curiosity that encourages them to pursue their passions in STEM and beyond.

References: [1] Bromm+, 2006, ApJ, 642, 382 [2] NAS, 2021, Astro2020 [3] Skinner, 2008, AO, 47, 2739 [4] Krimm+, 2013, ApJSS, 209,14 [5] Violette, 2022, Optimizing CdZnTe Detectors (Unpublished) [6] Allen, 2010, Proc. SPIE, 1009, 2824 [7] Tetarenko+, 2016, ApJS, 1512, 00778