Personal, Background, and Future Goals Statement

Background: From learning chess at age 5, to building computers at age 10, to solving Rubik's cubes at age 12, I have always fixated on understanding how things work and solving problems. Growing up in central Indiana, my high school had Purdue-educated engineering teachers to teach me digital electronics through Project Lead The Way and help me compete in the First Robotics Competition. As a member of our electronics team, I learned to bring motors to life and began seeing the world differently. Studying electronics let me understand our industrial world, but I knew I needed to study its foundation: physics. I was convinced that theory was my purpose, as spending each day theorizing the fundamentals of our universe seemed like the ultimate dream. Yet, missing my days of building robots, I realized I needed to use my hands as **I began using my electronics skills for instrumentation,** where I have found my place. The gratification of succeeding in the lab and the **knowledge I have gained from independent and collaborative research makes me confident a career in astrophysics instrumentation is my future.**

Intellectual Merit: I have designed and assembled printed circuit boards (PCBs) for directed high-energy projects propelling low-power wafer-scale spacecraft for the past year as part of my work under Dr. Philip Lubin. I found optimizing critical details like board traces which can create unwanted electromagnetic phenomena like parasitics and induced current to be captivating. These electronics are early steps towards interstellar flight which aims to send back data from the nearest stars and exoplanets. By the nature of spacecraft, reliability is essential. **I learned principles of meticulous engineering that are imperative to developing instrumentation capable of withstanding human error and the space environment.** For example, voltage regulators, bulk capacitors, and supervisor circuits (simple logic modules that monitor operating conditions) ensure the device will correct itself or turn off before damage occurs.

Concurrently, I have developed the software and astrophysics skills necessary for instrumentation in the Search for Directed Intelligence project. After two years of experience, I now co-lead the project looking for natural and artificial transients (sources that vary over human timescales) in optical and near-infrared wavelengths through a trillion-star survey of the Andromeda Galaxy and Magellanic Clouds. To this end, **I contributed significantly to the development of an original, modern image analysis pipeline for stellar transient detection.** This required constructing an efficient pipeline to align sources between images, create a normalized template for subtraction, extract and plot light curves from the resultant point source functions, and identify them in categories like RR Lyrae type stars, supernovae, or exoplanet transits. To meet the data storage and computational requirements of a large-scale survey, I assemble, upgrade, and maintain our research machines by installing hardware, backing up proprietary software, resolving software incompatibilities, and ensuring remote accessibility of these machines due to COVID-19. **Our research was awarded the NVIDIA Applied Research Accelerator Award which provided an NVIDIA RTX A6000, and I obtained six grants each for $750 from the Faculty Research Assistance Program to purchase additional hardware.** With this support, I use GPU-accelerated Fourier transformations to speed up image processing (currently 3 s per 6 Mpixel image) and I time the pipeline performance across a range of hardware. This work will be published in **an in-depth statistical analysis of our light curve creation toolset to be submitted in November.**

To gather data, Las Cumbres Observatory (LCO) awards our group 120 telescope hours annually to request deep space imaging, a vital and competitive resource critical to our research. In the past two years, I determined the ordering of survey objectives, identified known targets to recreate light curves for statistical analysis of our pipeline, created an organization system for 36,000 fits files, and scripted the sorting of the additional terabytes of data I requested and collected over more than 100 observations. With LCO, **I have navigated the complexities of scheduling telescope time** to ensure high-sensitivity observations (such as a rare exoplanet transit) are prioritized. In addition to LCO data, we are constructing an observatory atop the physics building (Broida Hall) to give undergraduates hands-on experience aligning telescopes and taking data. This observatory is built using hardware generously donated by LCO along with automation hardware and a low-cost tensor processing unit that can quickly process 26 Mpixel images using our pipeline. I am programming a pipeline module that preprocesses these images with flat-field corrections, applies noise reductions via bias/dark images, and adapts header data for our pipeline. **I hope to present early results in a planetary defense paper this December.**

I began contributing this spring to an alternative approach to image processing; a fast first-look, real-time source extraction method for transient detection. In this research to be published by next spring, we utilize a pre-trained convolutional neural network (YOLO Darknet) retrained to **identify ≤16th magnitude transient sources with ≥99% accuracy and ≥90% confidence.** This summer, I was supported by the NASA Space Grant program pursuing an extension to this observatory: an Extremely Large Scale High Cadence Sky Survey I will study in my senior thesis. By presenting the Broida Hall observatory as a scalable module, I will show **it is viable to image one trillion arcsecond^2 pixels in a real-time combined Earth- and space-based survey** finding supernovae and exo-planet occultations, contributing to multi-messenger physics (combining optical and gravitational wave data), and situational awareness for planetary defense. This survey targets one trillion pixels to ensure robust 4π steradian surveillance (~530 billion pixels) to overcome logistical details such as satellite flight paths, positioning Earth-based telescopes, overlapping FOV, etc. I will analyze the accuracy and timeliness of our pipeline compared to the state-of-the-art LSST pipeline for creating light curves from identical real datasets.

Broader Impact: Upon joining the Experimental Cosmology Group, disorganized and non-intuitive documentation impeded my ability to start working on the Search for Directed Intelligence project. This project is open to anyone interested in trying research and currently has more than thirty active undergraduates. After teaching myself the applicable libraries, I redesigned and began leading our onboarding process. I lead new project members, who usually have no prior experience with the required skills, learn Python, Astropy, Linux, Bash, Vim, and GitHub by mentoring new members individually and creating new documentation available anytime on our GitHub wiki. This mentorship ensures they do not become lost in our improved documentation and allows me to refine our documentation with their questions. Since these changes, new members begin contributing sooner, and those who leave our group pursue research in another topic of interest rather than being discouraged by the research process.

I continue sharing knowledge and learning from those around me outside my lab as an educator and mentor. Inspired by the mind of my elementary-aged sibling, I joined the UCSB Physics Circus in the fall of my freshman year, where we spark creativity through science nights at local elementary schools. With my freshman year shortened due to COVID-19, we moved online to continue creating exciting demonstrations like hammering nails with bananas frozen in liquid nitrogen. **We now serve classrooms throughout California with these demonstrations** during their science classes. That summer, I began co-developing the UCSB Physics Discord (a social messaging/VoIP platform) where professors and physics students of all levels and backgrounds socialize, study together, and advise one another.

With a physics degree conferral rate of around 20% over the past four years, most switch majors or drop out. Although UCSB Campus Learning Assistance Services (CLAS) only hires upperclassmen, I was motivated to increase success in physics and I was hired as a math and physics tutor as a sophomore. With CLAS, **I lead group sessions prioritizing student engagement and developing their intuition** and work individually with students who need extra help or advice about succeeding in their courses. As I graduate this winter, I plan to use my spring quarter tutoring full-time **for a total of ~1,200 hours with CLAS.** Working with Dr. Tengiz Bibilashvili, I began volunteering to assist a special relativity seminar I took as a freshman. After investing ~2.5 hours a week in these students for the past three years, I am now the lead assistant. Carrying forward my goal of improving degree conferral rates, I joined Undergraduate Diversity and Inclusivity in Physics to organize and volunteer for events that bring together and improve the physics community. To educate at all levels, I joined the UCSB Cub Support chapter of the UC-wide program to organize free weekly one-on-one math sessions with disadvantaged K-12 school students.

In order to counterbalance my research staring at stars on a monitor, I became an officer and founding member of the Astronomy Society in my junior year. We participate in amateur astronomy by hosting astronomy nights where we track objects in the night sky and listen to LCO staff and UCSB graduate student guest presentations. With the Astronomy Society, **I have spent two years engaging a general audience in astronomy.** At the same time, I mentored fifteen sophomore physics students (who had never been to campus due to COVID-19) in the UCSB Second-Year Flock Program. I helped these students acclimate to in-person physics classes and explore their interests by creating individualized course schedules for each student. Also based on their interests, I invited guest speakers to discuss research. **A year later, students are returning members of research groups I connected them to.** As an honors student, I also began individually mentoring freshman honors students. While group mentoring reaches more people, an upperclassman taking me under her wing sparked my research, and I strive to do the same for my mentees. When I was hired as a learning assistant (undergraduate TA) for the physics department, I co-led 40 4-hour lab sessions for 24 undergraduate students. In these labs, students created analog electronics circuits that evolved over the duration of the course from a simple LED to constructing a radio. In addition to labs, another assistant and I created numerous practice quizzes and co-led review sessions to ensure students understood the theory for their exams and futures in physics. With COVID-19 making socializing difficult, we kept the physics community alive by focusing Physics Discord on community building with online weekly study and game nights. During COVID-19, our community exploded **to over 2,200 UCSB physicists at all levels of study, including more than half of the faculty.** We have hosted 15 Q&A style professor interviews where students can gain insights into their research, personalities, and academic lives, many of which I organized during my time as secretary. As secretary, I partnered with officers in other clubs, professors, and physics department staff to announce events, along with job and research opportunities that our community jumped on. I am proud that our community better represents female-identifying students than the overall physics major at UCSB (24% vs. 19%) based on data from our opt-in pronoun system. Though opt-in surveys have sampling bias, 5 percentage points is significant and we feel this affirms we are achieving our day-one goal of a community that welcomes all.

Returning to my goal of improving low degree conferral rates, in my senior year I am using my tenure as UCSB Physics Discord president to **organize upcoming workshops in LaTeX, MATLAB, and Mathematica** for undergraduates who are unaware of these tools or do not know where to begin. These tools increased my success in classes and research and will hopefully enable more students to succeed. My team and I are also **filming and editing lab tours, creating a resource for undergraduate, and graduate students** deciding which labs to apply to and to learn about UCSB physics research. This summer, I volunteered as a learning assistant for a thermodynamics and statistical mechanics course to practice teaching upper division physics and help students succeed. I am working for the same course this fall, grading ~1,100 free response problems weekly and using my spare time to provide LaTeX support for those students interested in typesetting their work. As fall began, I discovered all UCSB Cub Support officers and more than half of the UCSB tutors had graduated. To fill this void, I volunteered as Co-lead where I navigated my chapter through the campus organization registration process and created new connections with the physics department and College of Creative Studies which had untapped supplies of qualified STEM tutors. I hope these connections will push membership higher this year enabling us to tutor a record number of underserved K-12 Students. Outside of traditional clubs, I joined Letters to a Pre-Scientists where I write letters to my yearlong 6th-grade pen pal. Her first letter asked great questions about seeing planets. Writing science for young students is a new experience, and I am excited to read what she thought of my letter and the artist renderings of exoplanet photos I mailed to her.

<u>Future Goals:</u> Support from the NSF and Professor Grindlay at Harvard University will enable me to use my instrumentation and astrophysics background to develop and characterize a wide-field coded X-ray telescope with an embedded pipeline as I pursue an astrophysics PhD. I will use my teaching experience to volunteer with Citizen Schools, **developing and teaching engaging curricula for underserved communities** that Citizen Schools have noted "lack the capacity, tools and training needed to provide rich, hands-on learning experiences." I will connect the Harvard–Smithsonian Center for Astrophysics Science Education Department (SED) to my volunteer work with Citizen Schools to include science demonstrations outside the scope of my research and archive my work online. I believe **including a broad range of scientific demonstrations will increase the impact of my curricula.** With SED's ability to publish my work online, **K-12 students globally can access my curricula** in a small step towards breaking down educational barriers that limit one's opportunity based on their location. After my graduate studies, I will complete postdoctoral research followed by teaching and research in transient detection instrumentation as a professor. Throughout my career, I will continue founding and joining organizations that address the obstacles that bar so many from their educational goals and inspiring K-12 scientists through presentations and teaching to create the next generation.

Uncovering High-Energy Transient Phenomena with Coded Aperture Imaging

<u>Background and Motivation:</u> 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.

<u>Research Project:</u> 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.

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

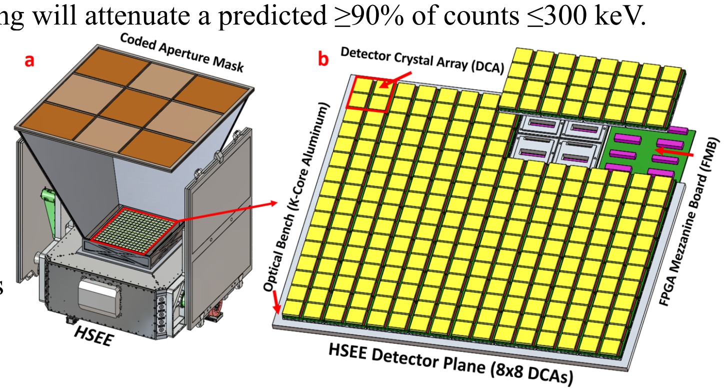

Fig. 1. a. CAD model of the HSEE detector
b. Exploded model of HSEE detector plane showing 256 DCAs on 64 FPGA mezzanine boards (Violette)

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.

<u>Intellectual Merit:</u> 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 bs [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.**

<u>Broader Impact:</u> 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.

<u>References:</u> [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