RESEARCH STATEMENT

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My research interests lie in understanding how the universe begins and evolves through the most energetic astrophysical explosions: gamma-ray bursts (GRBs), supernovae, merging of neutron stars and black holes. Many of these extraordinary events release their energy first in the form of high-energy photons, particles, and gravitational waves. My main research is carried out by utilizing data from high-energy (gamma-ray and X-ray) telescopes, in collaboration with ground-based observatories, neutrino detectors, and gravitational wave observatories. The main mission that I work with is the Neil Gehrels *Swift* Observatory (a.k.a. *Swift*), a multi-wavelength space telescope dedicated to studying GRBs and the transient sky.

A majority of my work involves supporting science operation of the Burst Alert telescope (BAT) onboard *Swift*. I work with the BAT team to compile the most recent catalog of GRBs detected by *Swift*/BAT (Lien & Sakamoto et al. 2016) and the hard x-ray source catalog from the past ~ 14 years of observation (Lien et al., in prep). I work closely with the original team that developed and built the BAT, designed the flight software and ground analysis pipeline, and continue to maintain and improve BAT operation.

While my graduate research of theoretical cosmology and particle astrophysics allows me to study the universe from the perspective of fundamental physics, working with the instrument team and performing data analysis has taught me the importance of understanding the instrumental behavior in order to successfully carry out relevant science projects. I am interested in combining my background in both theoretical studies and data analysis, to provide better connections of theoretical models to observational data through accurately handling instrumental/observational systematics and biases.

Almost all my research projects involve contributions from interns (mostly undergrads) at Goddard. My main research interests and future plans, along with student contributions are highlighted below.

Gamma-ray bursts (GRBs), supernovae, and gravitational waves

GRBs are one of the most energetic explosions in the universe. When a GRB occurs, it is often the brightest source in the entire gamma-ray sky. Due to the extreme brightness, GRBs are detected from within our local universe to the early universe. In fact, GRBs are one of the very few events that can be seen directly out to the era when the first generation stars were expected to form. GRBs are thus powerful tools to study the environment in the early universe, and how the universe has evolved to its current stage.

GRBs are usually classified into two groups, short and long, based on their burst durations, with the separation of about two seconds. Theoretical and observational evidence suggests that long GRBs originate from the collapse of massive stars, and thus are related to supernovae, while the short GRBs are from the mergers of two neutron stars, or a neutron star and a black hole, and therefore also produce gravitational waves.

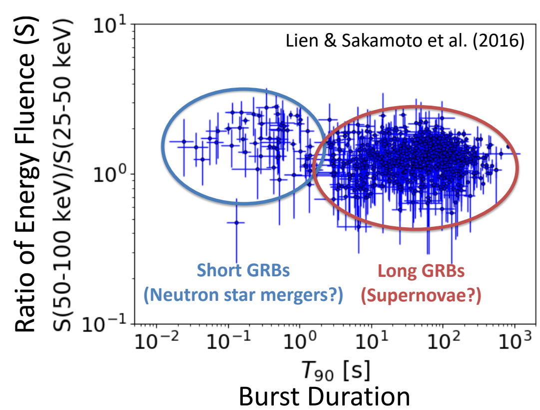

Figure 1: A summary of the spectral and temporal distribution of GRBs detected by *Swift*/BAT. Figure adapted from the 3rd BAT GRB catalog (Fig. 8 in Lien & Sakamoto et al. 2016).

While the gamma-ray emission usually only lasts for a few seconds to a few minutes, emission in the lower energy range can last for a much longer time (from days to years). In addition, GRBs are known sources of gravitational waves, and potential sources of neutrinos and cosmic rays. Therefore, to fully understand GRBs requires covering the "multi-messenger" astronomy with photons, neutrinos, cosmic rays, and gravitational waves.

Exploring the transient universe with the *Swift* Burst Alert Telescope (BAT)

Swift has been observing the transient sky for ~ 15 years. It has one wide field instrument, the Burst Alert Telescope (BAT), that detects GRBs in the gamma ray/hard x-ray range (15-350 keV), and two narrow field instruments, the X-Ray Telescopes (XRT) that collects photons in the soft x-ray range (0.2-10 keV), and the UV/Optical Telescope (UVOT) that observes in the UV and optical wavelengths (170-650 nm).

While gamma-ray instruments usually have a much larger field of view than lower energy instruments, they cannot provide good source localization because gamma-ray photons are too energetic to be easily reflected and focused on a single point. However, because GRBs occur randomly in the sky and the prompt emission only lasts for a short time ($\lesssim$ few hundred seconds), large field of view is crucial to increase the number of detections, while localization is important to allow follow up observations from the low-energy narrow-field instruments.

By utilizing the special "coded-mask technique" (e.g., Ables 1968, Feminore & Cannon 1978), BAT has the unique capability to cover a large field of view ($\sim$ 1/6 of the sky) and localize a source to $\sim$ few arcmin that enable followup observations. Fig. 2 demonstrates how to the coded-mask technique works to produce a sky image and background-subtracted light curves without actually focusing photons.

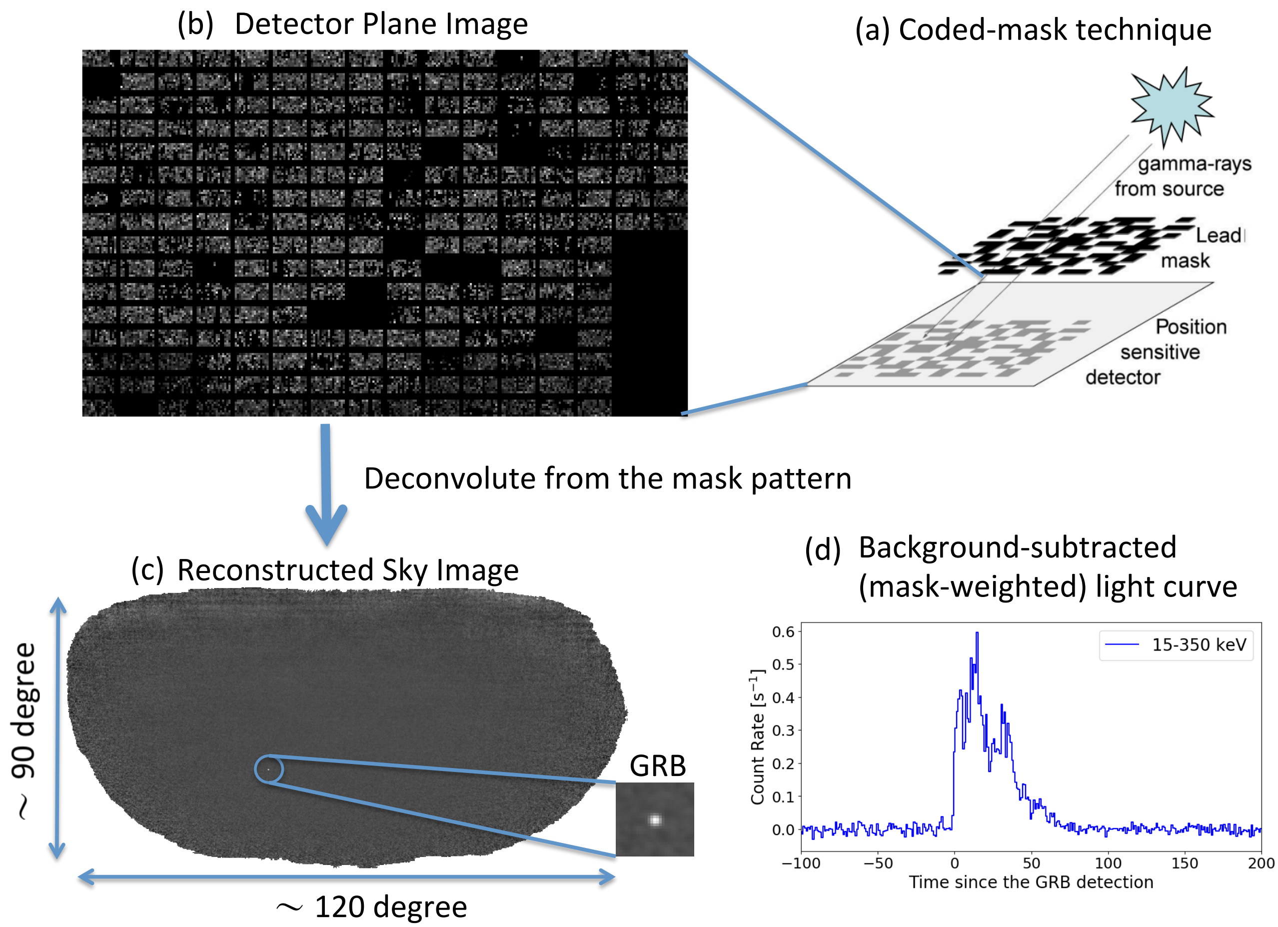

Figure 2: Demonstration of the coded-mask technique. The core of the coded-mask technique for gamma-ray/hard-X-ray instrument is a lead mask with a special pattern. The lead mask adopted by BAT can block high-energy photons up to $\sim$ 200 keV. Therefore, sources from a specific sky location will cast a unique shadow onto the detector plane through the lead mask, as illustrated in panel (a). By deconvoluting the detector plane image (panel b) and the mask pattern, one can reconstruct the source location and thus a sky image (panel c). Panel (b), (c), and (d) use data collected for GRB180111A, which is available at the BAT GRB catalog webpage (Lien & Sakamoto et al. 2016). The dark spots that appear on the detector plane image in panel (b) are detectors that were turned off during that time. As seen in panel (c), GRB180111A was the brightest source in the whole image. Panel (d) shows the "background subtracted" light curves using the mask-weighting technique that assigns a weighted value for each photon on the detector plane based on the shadow pattern from the GRB position.

Studying the observed GRB properties: The third *Swift*/BAT GRB catalog

For the past $\sim$ 15 years, BAT has detected more than 1300 GRBs, of which about 1/3 of GRBs have distance/redshift measurements from the ground observatories. I performed analyses for these GRBs and compiled the third Swift/BAT GRB catalog (Lien & Sakamoto et al. 2016). The result summaries and data products are available at the public website: `http://swift.gsfc.nasa.gov/results/batgrbcat/index.html`, which continues to be updated with recent bursts.

I worked with many undergraduates to utilize this substantial data set to study the observed GRB characteristics. Kevin Chen (University of California, Berkeley) compiled the list of GRBs with distance measurements to study observable signature for GRBs in the early universe. He co-authored in the paper Lien & Sakamoto et al. (2016). Jason Baron, Jared Hanley, and Fatimah Hussein (University of the Virgin Islands) searched for GRB pulse patterns in this catalog, which is a followup study of Hakkila et al. (2015). Austin Kim (University of Maryland at College Park) used these data to search for better criteria to quantify a good spectral fit.

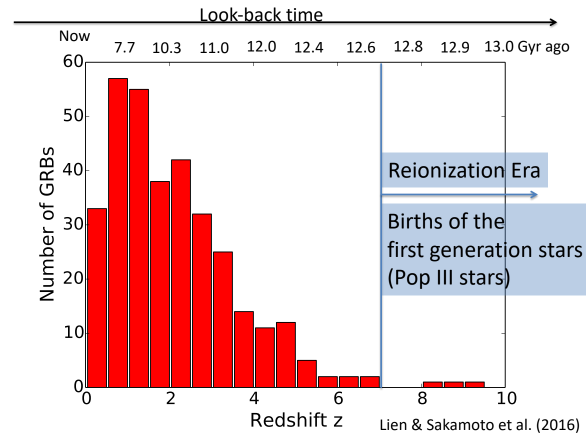

Figure 3: The GRB redshift/distance distribution adapted from the 3rd BAT GRB catalog (Fig. 22 in Lien & Sakamoto et al. 2016).

Probing the early universe with long GRBs

Because of their extreme brightness, long GRBs provide important insight of star-formation history in the early universe (Fig. 3). My research uses BAT data to estimate the cosmic GRB rate though careful simulations of the BAT detection algorithm (Lien et al. 2014). Fig. 4 summarizes the main results from this study.

To further constrain the uncertainty in our rate estimation, we adopted machine learning algorithms to mimic the trigger simulator and speed up the simulation process (Graff et al. 2016). The machine learning algorithms have become a powerful tool to perform studies in a wide range of subjects even beyond astrophysics. The ample of available open source packages makes it easy to adapt for an undergraduate study. An undergraduate intern, Anjali Mittu (University of Maryland), worked on this project and expanded the code to investigate star-formation rate based on different GRB distributions.

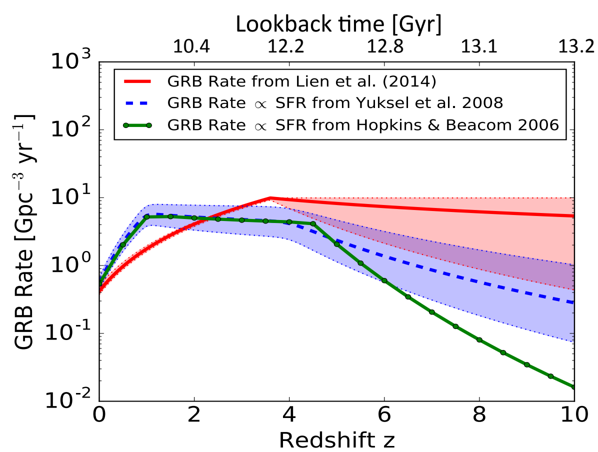

Figure 4: The GRB rate found in Lien et al. (2014) suggests a higher star-formation rate in the early universe than previously expected from galaxy observation. This figure is adapted from Fig. 17 in Lien et al. (2014).

Chasing gravitational wave counterparts in *Swift*/BAT

The discovery of the GRB associated with gravitational wave event GW170817 marks the significant breakthrough for multi-messenger astronomy and provides the first direct evidence that at least some short GRBs originate from neutron-star mergers (Abbott et al. PhRvL 2017, Abbott et al. ApJ 2017).

Swift has actively participated in the counterpart search and followup observations for gravitational waves detections. My work focuses on searching for potential astrophysical events in the BAT data around the gravitational wave detection time. Our search results are publicly available on the the BAT gravitational waves summary page (`http://swift.gsfc.nasa.gov/results/batgrbcat/index.html`), and also shared with the astronomy community through email notices via the Gamma-ray Coordinates Network (GCN). In addition, I worked with undergraduate interns, Charles Law (Harvard) and John Kerin (Georgetown University) to estimate short GRB detectability at different redshifts via simulations.

Connecting observations to theories: the Swift/BAT trigger simulator

In order to maximize the number of GRB detections, the BAT adopts a complex algorithm for finding GRBs, which includes over 600 search criteria. Although the method increased the chance of successfully finding GRBs, it also introduced an unknown and hard-to-quantify observational selection effect. To investigate this selection effect and explore the intrinsic GRB properties, we developed a pipeline that is capable of simulating the BAT trigger algorithm. This "trigger simulator" is used in many of our studies and undergraduate research, from exploring GRB intrinsic properties (source rate and luminosity) to examine the detectability of different X-ray transients, including GW170817. In addition, Mike Moss (a graduate student from the George Washington University) has been working with me since Summer 2018 and is leading a paper about the instrumental effects on the burst duration using this code.

Future observatories: exploring science potential and optimizing observing strategies

In addition to utilizing data from current space telescopes, I am interested in future observatories. My graduate study involves making predictions of supernova detections for future surveys, such as LSST (optical) and SKA (radio), and exploring possible ways to study high-energy astrophysics via synergies with multi-messenger observations, such as neutrinos (Super-Kamiokande) and gamma rays (*Fermi*). At Goddard, I am involved in several potential future space telescopes that include GRB science and searching for gravitational wave counterparts (e.g., TAO, TAP, AMEGO, BurstCube, Gamow, HSP). I perform simulations for GRB detections for these future missions, to search for optimal observing strategies and trigger algorithms that will maximize the detections for GRBs in the early universe and nearby short GRBs (i.e., potential counterparts of gravitational wave events).

Plans for future research

Understanding the GRB progenitors, emission mechanisms, and the corresponding observational properties

Although the long and short GRB classification has been widely adopted to imply the GRB origins (core collapse of massive stars vs. neutron stars/black holes mergers), the separation in the observational properties between these two classes remains vague and subject to instrumental biases (e.g., Lien & Sakamoto et al. 2016). This is not only troublesome for studying GRB origins and emission mechanisms, but it also introduces unknown biases when using GRBs to study star-formation history, and when searching for possible GRB signals accompanied with gravitational waves. I would like to work with undergraduates to extend my current studies and experiences in GRB observational properties and instrumental selection effects, to search for a better link between GRB observational properties and their origins. The undergraduates will utilize the trigger simulator to study observational characteristics for different theoretical models. During the process, students will learn the physics and observational features of GRBs, along with ample coding and data analysis skills, including machine learning algorithms and statistical methods.

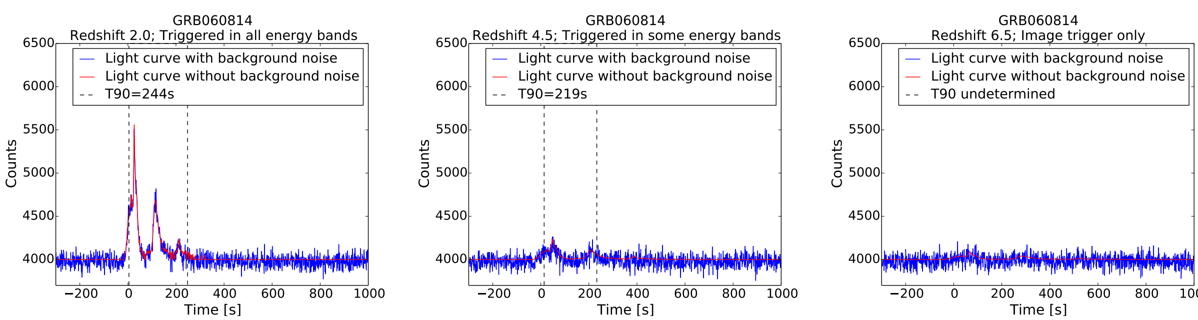

Figure 5: An example of the simulated light curve created from the *Swift*/BAT trigger simulator we developed. Different panels show the simulated light curves of the same burst at different redshifts/distances. I would like to continue to investigate observational signals from different theoretical assumptions (e.g., GRBs in the early universe, or from neutron-star mergers).

Exploring the early universe with GRBs

I am particularly interested in studying the early universe, especially with GRBs. As mentioned before, GRBs serve as an unique and independent probe to the early universe, and are complementary to other tools like supernovae and galaxies. I would like to expand my current work on star-formation history and use GRBs to study the environment in the early universe, such as metallicity, reionization, and galaxy evolution. Specifically, our previous studies have shown the importance of increasing the detections of GRBs in the early universe (Lien et al. 2014, Graff et al. 2016). Thus, I would like start with searching for possible observational characteristics that can be used for identifying these GRBs. I would like to study both the observational data and theoretical modeling of GRBs in the early universe with help from undergraduate students, and using our trigger simulator (or developing similar tools for other observatories) to connect models to observational signatures. Students will learn about cosmology and the early universe, and develop their own codes to perform modeling and simulations.

Understanding the noise: sub-threshold events in the era of multi-messenger astronomy

As we entering the era of multi-messenger astronomy, the astrophysics community is eager to utilize all the available data to have a complete picture of many mysterious astrophysical objects, such as the recently detected gravitational waves and the newly discovered fast-radio bursts (Lorimer et al. 2007).

However, the counterpart search remains challenging, as the transient occurrence is unpredictable and only lasts a very short time. To increase the chance of finding counterparts in other wavelengths/messengers, many studies have extended the search to the sub-threshold regime (i.e., signals that are slightly below the standard detection criteria) and develop sophisticated statistical tools to enhance these sub-threshold signals, such as finding coincidental sub-threshold detections in two observatories (e.g., the Astrophysical Multimessenger Observatory Network). However, this statistical approach also has its difficulties since many of the initial assumptions (e.g., the expected observational signals from the source) are uncertain.

I am interested in exploring the sub-threshold regime by developing a better understanding of the instrumental behavior and the associated noise. Using the sub-threshold data means encountering a higher chance of noise signals. It is thus crucial to understand the noise behavior to distinguish noise from real events. While the coded-mask technique is a brilliant method to achieve a large field of view while obtaining a decent localization, the "image" is created in a non-intuitive way and encodes complex systematics. As seen in Fig. 2, larger systematic noise appears at the edge of the image. I would like to explore possible ways to improve the instrument sensitivity in both BAT and potential future missions through better knowledge of coded-mask systematics. Students working on this project will gain detailed knowledge of the coded-mask technique and the computational/mathematical methods (e.g. Fast-Fourier transform and convolution), along with statistics analysis.

Detection algorithm for future missions

Another possibility to create an instrument with a large field of view and still be able to localize in hard X-ray is through the Lobster-eye optics (e.g. Peele et al. 1996). Several future missions that I am involved with adopt either the Lobster-eye optics or the coded-mask aperture. I plan to continue my work of the GRB simulations for these future surveys, and search for optimal detection algorithms. Students involved in these projects will have first-hand experience participating in the development phase of space telescopes, and learn about these instrumental techniques and simulations.

Beyond GRBs

Besides research topics that are directly related to GRBs, my interests go beyond things described above. I participate in various multi-messenger studies through BAT data analysis, such as the mysterious AT2018cow, which may be a white dwarf engulfed by a black hole (Kuin et al. 2019; presented at 2019 AAS Press Conference[1]), a multi-wavelength followup of S5 0716+714, the first blazar flare with coincidental neutrino detection (MAGIC Collaboration, 2018), and follow-up observations of a rare IceCube neutrino multiplet (IceCube Collaboration, 2017). In addition, the BAT hard X-ray survey catalog[2] that I am working on opened a new window of my research to other high-energy objects in the universe, such as active galactic nuclei (AGNs) and X-ray binaries.

I am excited about the opportunity to work at the XXX college, where I look forward to interacting with all the members and students, and exploring novel opportunities for collaboration.

[1] `https://www.youtube.com/watch?v=P8VhpMRxNW4`, including my presentation on behalf of the *Swift* team

[2] Preliminary results for the new BAT survey catalog are available `athttps://swift.gsfc.nasa.gov/results/bs157mon/`