Constraining intrinsic properties of gamma-ray bursts from core-collapse supernovae and neutron star mergers

Rachel Hamburg

Follow this and additional works at: https://louis.uah.edu/uah-dissertations

Recommended Citation
Hamburg, Rachel, "Constraining intrinsic properties of gamma-ray bursts from core-collapse supernovae and neutron star mergers" (2022). Dissertations. 255.
https://louis.uah.edu/uah-dissertations/255

This Dissertation is brought to you for free and open access by the UAH Electronic Theses and Dissertations at LOUIS. It has been accepted for inclusion in Dissertations by an authorized administrator of LOUIS.
CONSTRAINING INTRINSIC PROPERTIES OF
GAMMA-RAY BURSTS FROM CORE-COLLAPSE
SUPERNOVAE AND NEUTRON STAR MERGERS

by

RACHEL HAMBURG

A DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in
The Department of Space Science
to
The School of Graduate Studies
of
The University of Alabama in Huntsville

HUNTSVILLE, ALABAMA
2022
In presenting this dissertation in partial fulfillment of the requirements for a doctoral degree from The University of Alabama in Huntsville, I agree that the Library of this University shall make it freely available for inspection. I further agree that permission for extensive copying for scholarly purposes may be granted by my advisor or, in his/her absence, by the Chair of the Department or the Dean of the School of Graduate Studies. It is also understood that due recognition shall be given to me and to The University of Alabama in Huntsville in any scholarly use which may be made of any material in this dissertation.

[Signature]

Rachel Hamburg

10/31/22

(date)
Submitted by Rachel Hamburg in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Space Science and accepted on behalf of the Faculty of the School of Graduate Studies by the dissertation committee.

We, the undersigned members of the Graduate Faculty of The University of Alabama in Huntsville, certify that we have advised and/or supervised the candidate of the work described in this dissertation. We further certify that we have reviewed the dissertation manuscript and approve it in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Space Science.

Dr. Vladimir Florinski (Date)

Dr. Adam Goldstein (Date)

Dr. Michael S. Briggs (Date)

Haihong Che (Date)

Dr. Haihong Che (Date)

Dr. Gang Li (Date)

Dr. Judith Racusin (Date)

Dr. Gary P. Zank (Date)

Dr. Rainer Steinwandt (Date)

Dr. Jon Hakkila (Date)

iii
ABSTRACT

School of Graduate Studies
The University of Alabama in Huntsville

Degree Doctor of Philosophy College/Dept. Science/Space Science

Name of Candidate Rachel Hamburg

Title Constraining Intrinsic Properties of Gamma-ray Bursts from Core-collapse Supernovae and Neutron Star Mergers

Gamma-ray bursts (GRBs) are ultra-relativistic jets produced by either the core-collapse of massive, stripped envelope stars (i.e., “collapsars”) or the merging of compact binary objects, such as neutron stars. GRBs are among the most energetic transients in the Universe, yet despite over 5 decades of study, a full description of their intrinsic energetics remains incomplete. This is primarily due to a combination of cosmological, relativistic, and observational effects that have impeded obtaining GRB redshift measurements and robustly associating GRBs with their progenitors. In this dissertation, I study source-frame properties of GRBs from collapsars and binary neutron star (BNS) mergers. In particular, I constrain the luminosity functions and rate distributions of GRBs by applying a forward-folding method to fit data taken by the Fermi Gamma-ray Burst Monitor (GBM). The data are found to be best-fit with a GRB population composed of ~ 45% originating from BNS mergers. The collapsar GRBs are fit to the cosmic star formation rate, normalized to a local rate of $3.9_{-3.3}^{+9.9}$ Gpc$^{-3}$ yr$^{-1}$ and a broken power law luminosity function with indices $\alpha_L = -1.5_{-0.2}^{+1.1}$ and $\beta_L = -2.0_{-1.7}^{+0.5}$ and a break at $\log_{10} L = 52.8_{-3.2}^{+1.9}$ ergs s$^{-1}$. The merger GRBs
are described by a delayed star formation rate ($P(t_d) \propto t_d^{-1}$) with a local event rate of $3.2^{+27.0}_{-2.4}$ Gpc$^{-3}$ yr$^{-1}$ and a cut-off power law luminosity function with index $\alpha_L = -0.5^{+0.4}_{-0.5}$ and a break at $\log_{10} L = 51.6^{+0.7}_{-0.7}$ ergs s$^{-1}$. I also search for short GRB progenitors associated with GWs detected in the LIGO/Virgo first and second observing runs (i.e., O1 and O2, respectively). Although no GW/GRB coincidences are found other than GW170817/GRB 170817A, the GBM detection algorithm is improved for weak short GRBs and the joint search statistic method.
ACKNOWLEDGMENTS

First, I would like to give an enormous thank you to my research advisor, Adam Goldstein. He introduced me to the world of gamma-ray bursts when I was an undergraduate and has been a mentor ever since. He is the one of the most hard-working and down-to-earth scientists I know, and I consider myself lucky to have completed my graduate studies with him. I also want to give a heartfelt thank you to my UAH advisor Michael Briggs for his continual support and encouragement. As an early graduate student, he allowed me the freedom to explore different research topics and sent me to productive conferences in exciting places.

To the GBM team, I have so much gratitude for each one of you, and I cherish the time I’ve spent learning from and working with you all. I would like to thank Michelle Hui for coffee, chocolate, and career advice – often all at the same time and when I needed it most. A big thank you also goes to Cori Fletcher, who is both friend and co-worker and excellent at both. Thank you to Misty Giles for lunch breaks, distractions, and reminders that life is more than academia. A hearty thanks goes to Oli Roberts, Josh Woods, and Dan Kocevski – I’ve learned much from each of you. A very special thank you to my officemates and friends: Eric Burns, Matthew Stanbro, Suraj Poolakil, and Stephen Lesage. You guys made grad school so much more enjoyable, and I can only pray that my future officemates are as supportive and hilarious. I would also like to thank Colleen Wilson-Hodge and Valerie Connaughton for being excellent examples of female leadership in astrophysics; Tyson Littenberg for
informative and witty conversations; Rob Preece for all his support on the academic
side of things; Peter Veres for patiently answering all my theory questions, no matter
how naive; Chip Meegan and the late Bill Paciesas for trigger meeting fun; Bagrat
Mailyan for jokes and his inexplicable love of Decatur; Bill Cleveland for endearing
groupiness and help with computers/programming; Lisa Gibby for help getting data
when it could not be found; and, last but not least, Steve Elrod for encouraging emails
when work was tough.

To my friends and family: Dani, Jon, Dad, Austin, Qhapiya, Amy, Gabbie,
Sam, Marwa, Purva, Kelsey, Laura, Bev, Matt, and Patrick. You have made my life
so much richer, and I am grateful for all that we’ve shared together. You have seen
me through grad school, the loss of my mother, a global pandemic, and everything in
between. I could not have done any of this without your love and support.
TABLE OF CONTENTS

List of Figures xi
List of Tables xvi
List of Symbols xvii

Chapter

Introduction 1

1 History and Background 5

1.1 Cosmological Origin ........................................... 5
1.2 The Compactness Problem and Relativistic Motion ............... 8
1.3 GRB Progenitors ............................................... 12
  1.3.1 Core-collapse Supernovae .................................. 14
  1.3.2 Neutron Star Mergers ..................................... 17
1.4 Current Issues With GRB Classification .......................... 21

2 Physics and Intrinsic Properties of GRBs 25

2.1 The Physics of GRBs .......................................... 25
  2.1.1 Prompt Emission ......................................... 26
    2.1.1.1 The Fireball Model and Internal Shocks .............. 27
    2.1.1.2 GRB Spectra and Radiation Models .................. 29
2.1.2 Afterglow Emission ........................................ 34

2.2 Intrinsic Properties ........................................ 38
  2.2.1 GRB Redshift Distribution ............................... 38
  2.2.2 GRB Rate Density ........................................ 42
    2.2.2.1 Collapsar GRBs ..................................... 42
    2.2.2.2 Merger GRBs ....................................... 46
  2.2.3 GRB Luminosity Function ................................ 49

3 Paper in Progress: Constraining the Rate and Luminosity Function of *Fermi*-GBM GRBs

  3.1 Introduction ............................................... 52
  3.2 Instrument and Data ....................................... 55
    3.2.1 *Fermi* GBM .......................................... 55
    3.2.2 GBM Peak Flux Distribution ............................ 57
    3.2.3 GBM Luminosity Distribution ........................... 58
  3.3 Theoretical Framework .................................... 59
    3.3.1 GRB Luminosity Functions .............................. 59
    3.3.2 GRB Rate Densities ................................... 60
    3.3.3 GRB Peak Flux ........................................ 61
    3.3.4 GBM Detection Efficiency .............................. 62
  3.4 Bayesian Analysis ........................................ 64
    3.4.1 Likelihood ............................................ 66
    3.4.2 Priors ................................................ 68
4 Paper: A Joint Fermi-GBM and LIGO/Virgo Analysis of Compact Binary Mergers From the First and Second Gravitational-wave Observing Runs

4.1 Introduction ................................................. 85
4.2 Method .................................................... 88
   4.2.1 Gravitational-wave Trigger Selection ................. 88
   4.2.2 Fermi-GBM Searches .................................. 90
      4.2.2.1 Untargeted Search ............................... 92
      4.2.2.2 Targeted Search ................................. 93
4.3 Results .................................................. 94
   4.3.1 GBM Trigger and Untargeted Search Results .......... 96
   4.3.2 Targeted Search Results .............................. 98
   4.3.3 Targeted Search Joint Analysis ...................... 100
4.4 Summary and Future Directions ............................ 103

5 Conclusion .................................................. 105
References 107

APPENDIX A: Nested Sampling 157

APPENDIX B: Posterior Distributions From Fits to Simulations 159
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>The cumulative distribution of 140 BATSE GRBs as a function of peak photon count rate $C_{\text{max}}$ adapted from Meegan et al. (1992).</td>
</tr>
<tr>
<td>1.2</td>
<td>A sample of GRB lightcurves (50-300 keV) observed by the <em>Fermi</em> Gamma-ray Burst Monitor.</td>
</tr>
<tr>
<td>1.3</td>
<td>The count rate spectrum (left) and photon flux spectrum, $\nu F\nu$, (right) from fitting GRB 201412A to a Band function.</td>
</tr>
<tr>
<td>1.4</td>
<td>The BATSE $T_{\text{90}}$ distribution for GRBs in the 50–300 keV energy range from Kouveliotou et al. (1993).</td>
</tr>
<tr>
<td>1.5</td>
<td>A sample of 14 GRB afterglows and associated SNe lightcurves in the $R$-band taken from Cano et al. (2017).</td>
</tr>
<tr>
<td>1.6</td>
<td>Multi-messenger detection of GW170817 and GRB 170817A.</td>
</tr>
<tr>
<td>2.1</td>
<td>Cartoon illustrating the generic model of GRB formation and evolution (Gomboc, 2012).</td>
</tr>
<tr>
<td>2.2</td>
<td>GRB synchrotron spectrum from Sari et al. (1998) for a population of electrons accelerated by a relativistic shock.</td>
</tr>
<tr>
<td>2.3</td>
<td>Time-resolved model spectra of GRB 190114C from Ajello et al. (2020) using LAT and GBM data.</td>
</tr>
<tr>
<td>2.4</td>
<td>The GBM redshift (left) and luminosity (right) distributions from Poolakkil et al. (2021), spanning July 2008–June 2018.</td>
</tr>
<tr>
<td>2.5</td>
<td>Star formation rates and GRB rate as a function of redshift from Tanvir et al. (2021).</td>
</tr>
<tr>
<td>3.1</td>
<td>Simulated GBM detection probability as a function of peak photon flux (50-300 keV) for the 1024 ms timescale (purple) and the 64 ms timescale (tan).</td>
</tr>
</tbody>
</table>
3.2 Discrete probability density of $T_{90}$ measurements for all GRBs in the data sample and the timescales on which they triggered GBM. .... 64

3.3 Posterior probability distributions from using $R_{GRB}^{MF}$ and $\Phi_{BPL}^{C}$ for collapsar GRBs and $R_{GRB}^{BNS}$ and $\Phi_{CPL}^{M}$ for merger GRBs. ....... 72

3.4 Same as Figure 3.3 but for using the minimum luminosity of $1 \times 10^{49}$ ergs s$^{-1}$. ................................. 73

3.5 Predictive posterior distributions for the 1-s peak flux (left) and isotropic peak luminosity (right) distributions of GBM GRBs. ................. 74

3.6 The intrinsic and observed peak flux and luminosity distributions obtained using the parameter posterior medians of the $\Phi_{BPL}^{C} + \Phi_{CPL}^{M}$ ($\log_{10} L_{min} = 47$) model. ......................... 75

3.7 The rate density for GRBs from collapsars using the 90% parameter posterior credible intervals compared to the beaming corrected rate ($\theta_{j} = 5.4^\circ$) and the rate from Type Ibc SNe observations. ............... 77

3.8 The rate density for GRBs from BNS mergers using the 90% parameter posterior credible intervals compared to the beaming-corrected rate ($\theta_{j} = 10^\circ$) and that from GW observations of BNS mergers. ........... 78

4.1 Cumulative distribution for the minimal time offsets between the 25 CBC triggers and GRBs found by either the GBM onboard triggering algorithms or the Untargeted Search. ......... 95

4.2 O1 cumulative event rate distributions of the GBM background and search samples for the GBM Targeted Search as a function of the log-likelihood ratio. ................................. 97

4.3 O2 cumulative event rate distributions of the GBM background and search samples for the GBM Targeted Search as a function of the log-likelihood ratio. ................................. 98

4.4 Cumulative distribution of the Targeted Search p-values. ................. 102

B.1 The simulated and detected peak flux and luminosity distributions assuming the rate density $R_{GRB}^{BNS}$ and the luminosity function $\Phi_{CPL}$ with parameter values stated in the text. ............... 162
B.2 Posterior probability distributions from assuming $\Phi_{SPL}$ and $R_{GRB}^{MF}$ and fitting the simulated 1-s peak flux distribution of GRBs from collapsars.164

B.3 Posterior probability distributions from assuming $\Phi_{CPL}$ and $R_{GRB}^{MF}$ and fitting the simulated 1-s peak flux distribution of GRBs from collapsars.164

B.4 Posterior probability distributions from assuming $\Phi_{CPL}$ and $R_{GRB}^{MF}$ and fitting the simulated 1-s peak flux and luminosity distributions of GRBs from collapsars. 165

B.5 Posterior probability distributions from assuming $\Phi_{BPL}$ and $R_{GRB}^{MF}$ and fitting the simulated 1-s peak flux distribution of GRBs from collapsars.166

B.6 Posterior probability distributions from assuming $\Phi_{BPL}$ and $R_{GRB}^{MF}$ and fitting the simulated 1-s peak flux and luminosity distributions of GRBs from collapsars. 167

B.7 Posterior probability distributions from assuming $\Phi_{SPL}$ and $R_{GRB}^{WP}$ and fitting the simulated 1-s peak flux distribution of GRBs from collapsars.168

B.8 Posterior probability distributions from assuming $\Phi_{CPL}$ and $R_{GRB}^{WP}$ and fitting the simulated 1-s peak flux distribution of GRBs from collapsars.169

B.9 Posterior probability distributions from assuming $\Phi_{CPL}$ and $R_{GRB}^{WP}$ and fitting the simulated 1-s peak flux and luminosity distributions of GRBs from collapsars. 170

B.10 Posterior probability distributions from assuming $\Phi_{BPL}$ and $R_{GRB}^{WP}$ and fitting the simulated 1-s peak flux distribution of GRBs from collapsars.171

B.11 Posterior probability distributions from assuming $\Phi_{BPL}$ and $R_{GRB}^{WP}$ and fitting the simulated 1-s peak flux and luminosity distributions of GRBs from collapsars. 172

B.12 Posterior probability distributions from assuming $\Phi_{SPL}$ and $R_{GRB}^{BNS}$ and fitting the simulated 1-s peak flux distribution of GRBs from BNS mergers. 173

B.13 Posterior probability distributions from assuming $\Phi_{CPL}$ and $R_{GRB}^{BNS}$ and fitting the simulated 1-s peak flux distribution of GRBs from BNS mergers. 173

B.14 Same as Figure B.13 but using a peak flux threshold of 0.01 ph cm$^{-2}$ s$^{-1}$. 174

xiv
B.15 Posterior probability distributions from assuming $\Phi_{BPL}$ and $R_{GRB}^{BNS}$ and fitting the simulated 1-s peak flux distribution of GRBs from BNS mergers.

B.16 Same as Figure B.15 but using a peak flux threshold of 0.01 ph cm$^{-2}$ s$^{-1}$. 

175

176
## LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 GRB/SNe associations to GBM-detected GRBs.</td>
<td>16</td>
</tr>
<tr>
<td>2.1 GBM GRBs from July 2018–Present with redshifts</td>
<td>43</td>
</tr>
<tr>
<td>3.1 Prior distributions, descriptions, and symbols for the free parameters of the luminosity and rate density models.</td>
<td>68</td>
</tr>
<tr>
<td>3.2 Results from fitting the GBM 1-s peak flux distribution and peak luminosity distribution with the minimum luminosity of $1 \times 10^{47}$ ergs s$^{-1}$.</td>
<td>71</td>
</tr>
<tr>
<td>3.3 Same as Table 3.2 but using the minimum luminosity of $1 \times 10^{49}$ ergs s$^{-1}$.</td>
<td>71</td>
</tr>
<tr>
<td>4.1 Gravitational-wave triggers from Abbott et al. (2019a).</td>
<td>91</td>
</tr>
</tbody>
</table>
### LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>amplitude of GRB photon spectral model</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>low energy index of GRB photon spectral model</td>
</tr>
<tr>
<td>$\alpha_L$</td>
<td>low index of GRB luminosity function</td>
</tr>
<tr>
<td>$\alpha_z$</td>
<td>low index of GRB volumetric rate</td>
</tr>
<tr>
<td>$\beta$</td>
<td>high energy index of GRB photon spectral model</td>
</tr>
<tr>
<td>$\beta_L$</td>
<td>high index of GRB luminosity function</td>
</tr>
<tr>
<td>$\beta_z$</td>
<td>high index of GRB volumetric rate</td>
</tr>
<tr>
<td>$c$</td>
<td>speed of light</td>
</tr>
<tr>
<td>$D_C$</td>
<td>comoving distance</td>
</tr>
<tr>
<td>$D_L$</td>
<td>luminosity distance</td>
</tr>
<tr>
<td>$E$</td>
<td>gamma-ray energy</td>
</tr>
<tr>
<td>$E_c$</td>
<td>cutoff energy of GRB photon spectral model</td>
</tr>
<tr>
<td>$E_{iso}$</td>
<td>isotropic energy release in gamma rays</td>
</tr>
<tr>
<td>$E_0$</td>
<td>break energy of GRB photon spectral model</td>
</tr>
<tr>
<td>$E_p$</td>
<td>peak energy of GRB photon spectral model</td>
</tr>
<tr>
<td>$F$</td>
<td>gamma-ray flux</td>
</tr>
</tbody>
</table>
\( \Gamma \)  
bulk Lorentz factor

\( H_0 \)  
Hubble constant

\( L \)  
luminosity

\( L_{\text{c,}s} \)  
cut-off/break luminosity

\( \mathcal{L} \)  
Bayesian likelihood

\( \Lambda \)  
log-likelihood ratio

\( m_e \)  
mass of an electron

\( M_\odot \)  
mass of the Sun

\( n_\gamma \)  
gamma-ray efficiency

\( P \)  
gamma-ray peak flux

\( p \)  
spectral index of electron distribution

\( \pi \)  
Bayesian prior

\( \rho_0 \)  
local GRB rate density

\( \sigma_T \)  
Thompson cross-section

\( \theta_b \)  
relativistic beaming angle

\( \theta_j \)  
GRB jet half-opening angle

\( t_d \)  
time delay between BNS formation and merger

\( t_j \)  
observed time of jet break

\( T_{90} \)  
GRB duration measure

xviii
$Z$  Bayesian evidence

$z$  redshift

$z_*$  break redshift of GRB volumetric rate
For my mother,

Sabrina Ann Hamburg
INTRODUCTION

Gamma-ray bursts (GRBs) are the most brilliant signatures of stellar death in the Universe. GRBs are ultra-relativistic ($\Gamma \gtrsim 100$) jets observed as a bright flash of gamma rays lasting between fractions of a second up to a few minutes. They occur at unpredictable times, from random locations on the sky, and are formed through two main channels: the core-collapse of massive ($\gtrsim 30M_\odot$), stripped-envelope stars (i.e., “collapsars”; MacFadyen and Woosley 1999) and the merging of binary compact objects, like neutron stars (Eichler et al., 1989; Narayan et al., 1992). GRBs are unique as they are one of the few objects to be observed at high redshifts ($z > 8$; e.g., Tanvir et al. (2009), Cucchiara et al. (2011)), making them excellent tools for probing early cosmic evolution. Interestingly, GRBs have even been suggested as having a role in mass extinction of Life, both here on Earth and across the Universe (Melott et al., 2004; Piran and Jimenez, 2014).

In recent years, GRBs have played a key part in the rapidly growing field of multi-messenger astronomy, or the study of astrophysical events using more than one “messenger” (i.e., gravitational waves (GWs), photons, neutrinos, and cosmic rays). One of the most spectacular multimessenger events took place on August 17, 2017, when the first binary neutron star (BNS) merger was detected in GWs (Abbott et al., 2017c, 2019b) and the associated gamma-ray burst, GRB 170817A\(^1\), was

\(^{1}\)GRBs are named according to the date on which they were detected (i.e., GRB YYMMDD). Letters starting from “A” are also appended to the end in order to differentiate between GRBs occurring on the same day.
observed ∼ 1.7 seconds later (Goldstein et al., 2017). This joint detection (Abbott et al., 2017a) confirmed the long-standing suspicion that BNS mergers are progenitors of short GRBs, or GRBs with observed durations of less than 2 seconds. This event also lead to ground-breaking science, such as the first measure of the speed at which GWs travel (Abbott et al., 2017a), an independent constraint on the Hubble constant (Abbott et al., 2017; Hotokezaka et al., 2019), the first unambiguous discovery of a kilonova, and the first direct evidence for r-process nucleosynthesis (Chornock et al., 2017; Cowperthwaite et al., 2017; Kasen et al., 2017; Tanvir et al., 2017; Watson et al., 2019). Altogether, these observations constructed the single most comprehensive description of the physical processes at play in BNS mergers and their electromagnetic (EM) counterparts. This was only one event, but there are still many open questions about the nature of GRBs. For example, What mechanisms produce the extreme energies observed in GRBs? What is the distribution of GRB luminosities, and how is it affected when considering the angular profiles of GRB jets? What is the relationship between progenitor mass, remnant type, and GRB emission properties? What conditions are necessary for collapsars and BNS mergers to produce GRBs? What is the intrinsic rate distribution of GRBs and can it inform the cosmic star formation rate, particularly at high redshift? Are there other progenitors that produce GRBs, such as neutron star-black hole mergers? What part do neutrinos play in GRB emission processes?

Answers to the above questions have been difficult to find. Although more than 6,000 GRBs have been detected since their discovery, less than ∼ 5% have robust redshift measurements and even fewer have been associated with a progenitor.
The lack of distance measurements and observed progenitor properties, as well as the complex nature of GRB spectra, has made it difficult to fully understand GRBs.

Yet the future is bright. In the past 5 years, there has been a rise in the number of GRB redshift measurements—primarily due to increasingly sensitive optical surveys such as the Zwicky Transient Factory (ZTF; Bellm et al. (2019)) and world-wide optical networks like the Global Relay of Observatories Watching Transients Happen (GROWTH) project (Kasliwal et al., 2019). The Vera C. Rubin Observatory (Ivezić et al., 2019), which will survey the entire Southern sky at a cadence of a few days, will also see first light in ~2023. Additionally, future upgrades to the GW detector network (Abbott et al., 2020b) will lead to an increasing number of joint detections between GRBs and BNS mergers (Beniamini et al., 2018; Howell et al., 2019).

In this dissertation, the source-frame properties of GRBs from collapsars and BNS mergers are studied. In particular, the luminosity functions and rate distributions of GRBs are constrained by applying a forward-folding method to fit data taken by the Fermi Gamma-ray Burst Monitor (GBM). The data are found to be best-fit with GRB population composed of ~45% originating from BNS mergers. The collapsar GRBs are fit to the SFR from Madau and Fragos (2017), normalized to a local rate of $3.9^{+0.9}_{-3.3}$ Gpc$^{-3}$ yr$^{-1}$ and a broken power law luminosity function with indices $\alpha_L = -1.5^{+1.1}_{-0.2}$ and $\beta_L = -2.0^{+0.5}_{-1.7}$ and a break at $6.2^{+495.}_{-6162.} \times 10^{52}$ ergs s$^{-1}$. The merger GRBs are described by a delayed star formation rate ($P(t_d) \propto t_d^{-1}$) with a local event rate of $3.2^{+27.0}_{-2.4}$ Gpc$^{-3}$ yr$^{-1}$ and a cut-off power law luminosity function with index $\alpha_L = -0.5^{+0.4}_{-0.5}$ and a break at $4.3^{+18.6}_{-6_{3.5}} \times 10^{51}$ ergs s$^{-1}$. To help constrain GRB properties from BNS mergers in particular, I also search for short GRB pro-
genitors associated with GWs detected in the LIGO/Virgo first and second observing runs (i.e., O1 and O2, respectively). Although no GW/GRB coincidences are found other than GW170817/GRB 170817A, the GBM detection algorithm is improved for weak short GRBs and the joint search statistic method.

The structure of this dissertation is as follows. Chapter 1 further details the history and background of GRBs, and Chapter 2 summarizes the physics of GRBs and what is currently known about their intrinsic properties. The theoretical framework, method, and results of fitting the GRB luminosity and rate distributions are presented in Chapter 3. In Chapter 4, a search for gamma-ray signals associated to compact binary mergers detected during O1 and O2 is also presented. Finally, in Chapter 5, I summarize this dissertation and discuss prospects for future work.
CHAPTER 1

HISTORY AND BACKGROUND

GRBs were serendipitously discovered in the late 1960s by the US Vela satellites, which were launched to monitor Soviet Union compliance to the 1963 Partial Nuclear Test Ban Treaty (Singer, 1965). Between 1969 and 1972, the Vela satellites identified 16 bursts of gamma-ray photons in the 200 keV–1.5 MeV range. However, the bursts did not originate from the Earth or the Sun, and did not appear to be correlated with any known astrophysical object (Klebesadel et al., 1973). These mysterious gamma-ray bursts were subsequently determined to be a new and unique phenomenon. In this chapter, I summarize the history and fundamental knowledge of GRBs. The discovery of the cosmological origin of GRBs is presented in Section 1.1, and the relativistic nature of GRBs is discussed in Section 1.2. Section 1.3 introduces the known types of GRB progenitors, and in Section 1.4, the standard GRB classification method is challenged.

1.1 Cosmological Origin

The first instrument dedicated to the detection and study of GRBs was the Burst And Transient Source Experiment (BATSE; Fishman (1992)) onboard the
Compton Gamma-Ray Observatory – one of NASA’s “Great Observatories.” BATSE observations between 1991 and 2000 revealed the first key features of GRBs. One of the first major discoveries was that GRBs are isotropically distributed across the sky, with no preference towards the Galactic plane (Meegan et al., 1992). If GRBs are of Galactic origin, this could be interpreted in two ways: (1) BATSE was observing GRBs to a distance much less than the length scale of the source distribution (e.g., inside a “bubble” of GRB sources) or (2) BATSE was observing GRBs to a distance greater than the length scale of the source distribution but was located close to its center (e.g., GRBs originating from a Galactic halo). On the other hand, if GRBs are of extragalactic origin, an isotropic distribution is the natural result. Homogeneity tests were then used to shed light on the spatial distribution of GRBs (Briggs, 1993; Briggs et al., 1996).

Assuming a uniform sphere of GRBs in Euclidean space and that each GRB has the same intrinsic energy $E$, the distance $r$ to each GRB with fluence $S$ is defined as:

$$r(S) = \left( \frac{E}{4\pi S} \right)^{1/2} \quad (1.1)$$

Given a particular value of fluence ($S^*$), all GRB sources within the sphere at radius $r(S^*)$ will have a fluence $S$ greater than $S^*$. With $n$ sources per unit volume, the number of GRBs within this radius are

$$N(S) = n \frac{4\pi}{3} \left( \frac{E}{4\pi S} \right)^{3/2} \quad (1.2)$$
Figure 1.1: The cumulative distribution of 140 BATSE GRBs as a function of peak photon count rate $C_{\text{max}}$ (a proxy for peak photon flux), adapted from Meegan et al. (1992). A power law of $-3/2$ is expected for a homogenous spatial distribution of GRB sources.

Therefore, the number of GRBs versus fluence should follow a $-3/2$ power law if GRBs are uniformly distributed in Euclidean space. As can be seen in Figure 1.1, the BATSE sample shows a significant lack of low-fluence GRBs from that expected from a homogenous distribution. Under the Galactic origin assumption, this is inconsistent with the idea that BATSE was detecting GRBs within the length scale of the source distribution, favoring Galactic halo models instead. Under the extragalactic origin assumption, the inhomogeneity is interpreted as being due to the non-Euclidean geometry of space, GRB source evolution, or a combination of the two. Consequentially, further evidence was needed to determine GRB origins.

In 1997, the Italian-Dutch X-ray satellite BeppoSAX (Boella et al., 1997) identified fast-fading X-ray emission from GRB 970508 (Costa et al., 1997a). This was
identified as the GRB afterglow. Afterglows are more smoothly-varying counterparts that can be seen at all wavelengths and arise from interactions between GRBs and the interstellar medium (ISM). The first GRB afterglow was discovered by BeppoSAX in coincidence with GRB 970228 (Costa et al., 1997b) only a few months earlier. In the case of GRB 970508, the arc-minute localization enabled deep follow-up by optical telescopes on the ground, and spectroscopic observations led to the identification of a host galaxy and a redshift measurement of $z \sim 0.85$ (Metzger et al., 1997). This confirmed that GRBs have an extragalactic origin – a conclusion that was further established after the launch of the *Neil Gehrels Swift Observatory* (Gehrels et al., 2004) in 2004. With its suite of onboard gamma-ray, X-ray, UV, and optical instruments, *Swift* has the capability to detect and localize GRB afterglows down to sub-arcsecond precision, which has led to many host galaxy associations and redshift measurements for GRBs.

### 1.2 The Compactness Problem and Relativistic Motion

The extragalactic origin of GRBs initially posed a challenge: at such large distances GRBs would have enormous source energetics of $\gtrsim 10^{50}$ ergs. When combined with inferences from GRB lightcurves and spectra, this leads to the *compactness problem*, or a tension between the expected optically-thick emission and the observed non-thermal spectra of GRBs (Cavallo and Rees, 1978; Fenimore et al., 1993; Schmidt, 1978). The tension is explained as follows. GRB lightcurves exhibit diverse temporal behavior (Figure 1.2), and individual pulses can vary rapidly on the order of milliseconds (Nemiroff et al., 1993). The observed variability timescale is related to the
Figure 1.2: A sample of GRB lightcurves (50-300 keV) observed by the Fermi Gamma-ray Burst Monitor. Produced using the GBM Data Tools (Goldstein et al., 2021).

light-crossing time of the emitting region and points to compact source sizes $c\Delta t \sim 10^3$ km, suggesting neutron star or black hole central engines.

A consequence of very high luminosity and compact source size is that the outflow is expected to be dense and optically-thick to gamma-rays in the upper keV to MeV range. Photons with combined energies above $\sim 1$ MeV will predominately produce electron-positron pairs via $\gamma + \gamma \rightarrow e^+e^-$. If the source spectrum is not strongly peaked, higher energy gamma-rays will form pairs primarily with lower en-
ergy gamma-rays, and the resultant pairs will eventually annihilate to form photons around 511 keV. Thus, the spectrum quickly becomes diminished above \( \sim 1 \text{ MeV} \). Observations of large flux from GRBs in the MeV band are therefore not expected, unless the optical depth to pair production is \(< 1\). From Piran (1999), the average optical depth for pair production can be expressed as

\[
\tau_{\gamma\gamma} = \frac{f_p \sigma_T S D_L^2}{R^2 m_e c^2}
\]

where \( f_p \) is the fraction of photons available to pair-produce, \( \sigma_T \) is the Thompson cross-section, \( D_L \) is the luminosity distance, and \( R \) is the emission radius. For a compact (\( \sim 10^3 \) km) object with high fluence (\( \sim 10^{-7} \) ergs cm\(^{-2} \)) at a cosmological distance (\( z \sim 0.5 \)), the optical depth is on the order of \( 10^{13} \), and the spectra should be characterized by thermal radiation. As can be seen in Figure 1.3, GRB spectra clearly indicate non-thermal radiation, with the bulk of the gamma-ray power lying around a few hundred keV and often showing tails extending well into the MeV band.

The compactness problem is resolved with the inclusion of relativistic effects. Relativistic effects ease the requirements on the total energy and yield larger radii at which the emission can be generated. More specifically, relativistically moving material can be described by the bulk Lorentz factor \( \Gamma = 1/\sqrt{1 - (v/c)^2} \), where \( v \) is the average co-moving velocity of outflow. The rest-frame emission radius is increased by \( \Gamma^2 \), and the observed photon energies are also blue-shifted by a factor \( \Gamma \). Given the shift in energy, there are also fewer gamma-rays available to pair-produce. This decreases \( f_p \) by \( \Gamma^{2\alpha} \), where \( \alpha \) is the spectral index of the source photon spectrum. The
optical depth to pair-production $\tau_{\gamma\gamma}$ from above becomes $\sim 10^{13}/\Gamma^{4+2\alpha}$, meaning the compactness problem is resolved if GRBs move ultra-relativistic speeds of $\Gamma \approx 10^2$. This is faster than any other known astrophysical object, as only the brightest AGN jets have Lorentz factors of $\leq 50$ (Homan, 2012).

Another important effect of relativistic motion is that portion of GRBs visible to the observer are beamed into an angle $\theta_b = 1/\Gamma$. For narrow, bi-polar jets with half-opening angle $\theta_j$, the total isotropic energy is lowered by $(1 - \cos \theta_j) \approx \theta_j^2/2$. Thus, for a collimated relativistic outflow, an observer will initially see emission from only a small portion of the jet, $\theta_b$, that is beamed into the observer’s line of sight. Once the jet begins to interact with the surrounding medium and slow down, $\theta_b$ will increase until it becomes as large as $\theta_j$ – at which point the edge of the jet becomes discernible by the observer, and the flux drops at all wavelengths (Frail et al., 2001; Rhoads, 1999; Sari et al., 1999). An achromatic jet break was first detected in the afterglow lightcurve of GRB 990510, confirming the nature of collimated jets in GRBs.
(Harrison et al., 1999; Stanek et al., 1999). Since then, jet breaks have been discovered in a number of GRBs (Fong et al., 2015; Racusin et al., 2009).

It is necessary to note that jet breaks such as those described above are valid only for top-hat GRB models, in which the energy density and Lorentz factor are constant across $\theta_j$ and drop rapidly outside this angle. However if the GRB occurs within a dense environment, interactions between the jet and the surrounding medium likely shape the angular distribution of the energy density and Lorentz factor (Lamb et al., 2021; Salafia et al., 2015, 2020). GRB jets could also be launched with an intrinsic jet structure. Nonetheless, when observed near the jet axis, the top-hat model can well explain prompt and afterglow observations, but when viewed from larger angles, more complex models are needed to explain the observed energies (e.g., Abbott et al. 2017a; Howell et al. 2019). These structured jet models have large implications for GRB rates and luminosity functions (e.g., Hayes et al. 2020).

1.3 GRB Progenitors

Another major finding from the BATSE era is that GRBs are clustered into two groups based on their $T_{90}$, or the time during which 5-95% of the cumulative photon flux is observed (Dezalay et al., 1992; Kouveliotou et al., 1993). GRBs with durations less than two seconds (i.e., $T_{90} < 2s$) are designated as “short,” while those with durations greater than two seconds (i.e., $T_{90} > 2s$) are called “long” (Figure 1.4). The BATSE $T_{90}$ distribution was the first evidence that GRBs have at least two progenitors.
Spectral observations of GRBs reveal additional bimodalities. The ratio between hard (100-300 keV) and soft (50-100 keV) photons is higher on average for short GRBs (Kouveliotou et al., 1993), implying the energy release differs between the two classes and that each class is produced by a different source. Furthermore, bright GRBs are often well-fit by the phenomenological Band function (Band et al., 1993), and the peak energies in $\nu F\nu$ space, $E_p$, are typically $\sim 500$ keV for short GRBs and $\sim 200$ keV for long GRBs (Poolakkil et al., 2021).

Studies of GRB environments also support the idea of two different progenitors. Long GRBs are found in spiral and irregular galaxies with high star formation rates (SFRs) and lower metallicity, while short GRBs occur in both early- and late-type galaxies with lower star formation and older stellar populations (Fruchter et al., 2006; Graham and Fruchter, 2013; Nugent et al., 2022). Long GRBs also reside closer to the center of their host galaxies than short GRBs (Fong and Berger, 2013) and follow a spatial distribution consistent with that of massive stars (Bloom et al., 2002).
1.3.1 Core-collapse Supernovae

The first clear connection between GRBs and a progenitor came in 1998 with the detections of GRB 980425 and supernova SN1998bw.\(^1\) SN1998bw was found within the localization box of GRB 980425 \(T_{90} \sim 23\) s within one day after the GRB detection (Galama et al., 1998). The localization also coincided with the barred spiral galaxy ESO 184-G82 at \(z=0.0085\) (Tinney, 1998). From the lack of H and He I and the weak presence of Si II in the spectra, SN1998bw was classified as Type Ic, indicating core-collapse of a massive \((\geq 40 M_\odot)\) star (Galama et al., 1998; Patat and Piemonte, 1998). The early-time SN luminosity \(M_v \sim -19.35\) was unusually high, and the emission lines were broad, inferring huge expansion velocities of \(\sim 30,000\) km/s (Patat et al., 2001). The estimated kinetic energy of \(\sim 10^{52}\) ergs was also more than 10 times higher than that of previously known SNe (Iwamoto et al., 1998). Interestingly, the GRB luminosity was unexpectedly low at \(\sim 5 \times 10^{46}\) ergs.

Altogether, these observations implied that GRB 980425 had been formed by a rare kind of core-collapse supernova (Iwamoto et al., 1998; Woosley et al., 1999). Even so, the chance coincidence of GRB 980425 and SN1998bw was conservative due to the low flux of the GRB afterglow (Galama et al., 1999).

Since GRB 980425/SN1998bw, tens of SN have been connected with long GRBs (Cano et al., 2017; Hjorth and Bloom, 2012). There are 17 GRBs observed by GBM that have been associated with a SN. The GRBs, their \(T_{90}\) durations, redshifts, peak luminosities (10-1000 keV), and associated SNe are detailed in Table 1.1. For

\(^1\)Supernovae are named by the year in which they are discovered with \(1^+\) letters added according to when they occurred (i.e., the first 26 SNe discovered in 2019 are named SN2019a through SN2019z, and the next 26 will be assigned SN2019aa to SN2019az.)
GRB 201015A, I use the spectral fit reported in (Fletcher et al., 2017; GCN 28663) to derive the peak luminosity. For GRBs 180728A, 190829A, 200826A, and 211023A, I perform spectral fits with the Band function over the brightest time bin, using ≤ 3 GBM NaI detectors with good detector-viewing angles (< 60° and the BGO detector with the smallest viewing angle. The brightest time bin is chosen to be the 1-s bin with the highest signal-to-noise ratio in the NaI detector with the smallest viewing angle.

The smoking gun signature for a GRB/SN association is a rising “SN bump” in the late-time afterglow lightcurve (Figure 1.5). The SNe that have been associated with GRBs are all Type Ic. They show broader absorption lines and have larger kinetic energies than those of Type Ic SNe not associated with GRBs (Cano et al., 2017) and are preferentially found in low metallicity environments (Graham and Fruchter, 2013).

<table>
<thead>
<tr>
<th>GRB</th>
<th>( T_{90} ) (s)</th>
<th>( z )</th>
<th>( L ) (ergs s(^{-1}))</th>
<th>SN</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>081007</td>
<td>10.*</td>
<td>0.53</td>
<td>3.82e+50</td>
<td>2008hw</td>
<td>[1],[2]</td>
</tr>
<tr>
<td>090618</td>
<td>112.39</td>
<td>0.54</td>
<td>2.02e+52</td>
<td></td>
<td>[1],[2]</td>
</tr>
<tr>
<td>091127</td>
<td>8.70</td>
<td>0.49</td>
<td>7.51e+51</td>
<td>2009nz</td>
<td>[1],[2]</td>
</tr>
<tr>
<td>101219B</td>
<td>51.01</td>
<td>0.55</td>
<td>2.70e+50</td>
<td>2010ma</td>
<td>[1],[2]</td>
</tr>
<tr>
<td>111228A</td>
<td>99.84</td>
<td>0.71</td>
<td>2.26e+51</td>
<td>2008hw</td>
<td>[1],[2]</td>
</tr>
<tr>
<td>120729A</td>
<td>25.47</td>
<td>0.8</td>
<td>5.76e+51</td>
<td></td>
<td>[1],[2]</td>
</tr>
<tr>
<td>130215A</td>
<td>143.75</td>
<td>0.6</td>
<td>2.11e+51</td>
<td>2013cz</td>
<td>[1],[2]</td>
</tr>
<tr>
<td>130427A</td>
<td>138.24</td>
<td>0.34</td>
<td>1.32e+53</td>
<td>2013cq</td>
<td>[1],[2]</td>
</tr>
<tr>
<td>130702A</td>
<td>58.88</td>
<td>0.15</td>
<td>1.64e+50</td>
<td>2013dx</td>
<td>[1],[2]</td>
</tr>
<tr>
<td>140606B</td>
<td>22.78</td>
<td>0.38</td>
<td>1.76e+51</td>
<td></td>
<td>[1],[2]</td>
</tr>
<tr>
<td>171010A</td>
<td>107.27</td>
<td>0.33</td>
<td>9.50e+51</td>
<td>2017htp</td>
<td>[2],[3],[4],[5]</td>
</tr>
<tr>
<td>180728A</td>
<td>6.40</td>
<td>0.117</td>
<td>8.12e+50</td>
<td>2018fip</td>
<td>[6],[7]</td>
</tr>
<tr>
<td>190114C</td>
<td>116.35</td>
<td>0.42</td>
<td>1.07e+53</td>
<td>2019jrg</td>
<td>[8],[9]</td>
</tr>
<tr>
<td>190829A</td>
<td>59.39</td>
<td>0.078</td>
<td>4.04e+49</td>
<td>2019oyw</td>
<td>[10],[11]</td>
</tr>
<tr>
<td>200826A</td>
<td>1.14</td>
<td>0.748</td>
<td>1.38e+52</td>
<td></td>
<td>[12],[13]</td>
</tr>
<tr>
<td>201015A</td>
<td>9.78*</td>
<td>0.426</td>
<td>2.02e+50</td>
<td></td>
<td>[14],[15]</td>
</tr>
<tr>
<td>211023A</td>
<td>79.11</td>
<td>0.390</td>
<td>1.99e+51</td>
<td></td>
<td>[16],[17]</td>
</tr>
</tbody>
</table>

One mystery surrounding the GRB-SN connection is why so few Type Ic SNe lead to GRBs. Even when considering observational biases, the inferred local rate of long GRBs is orders of magnitude lower than that of Type Ic SNe (e.g., Gal-Yam et al. 2006; Lien et al. 2014; Wanderman and Piran 2010). The answer may lie in the
properties of their central engines. It is thought that GRB-SNe are driven by hyper-accreting black holes or rapidly-rotating magnetars created during core-collapse of massive (> 30 M\(_{\odot}\)) stars (MacFadyen and Woosley, 1999; Woosley, 1993). High angular momentum in these systems is a necessary factor for GRB jet production (MacFadyen and Woosley, 1999; Woosley and Bloom, 2006), and special conditions are likely required to sustain such rotation at the end of a star’s life (Zhang, 2018).

1.3.2 Neutron Star Mergers

Since the discovery of GRBs, binary neutron star (BNS) and neutron-star/black hole (NSBH) mergers have been suggested as GRB progenitors (Eichler et al., 1989; Nakar, 2007; Narayan et al., 1992). BNS and NSBH mergers can power electromagnetic outflows with energies \(\geq 10^{50}\) ergs, and the large host galaxy offsets observed in short GRBs can be explained as due to natal kicks, or increased velocities imparted to neutron stars when their progenitor stars undergo supernova explosions (Fong and Berger, 2013). Natal kicks can provide the binary with the momentum to travel large distances. A compact binary origin also explains why short GRBs are found in regions of lower star formation and older stellar populations, since it takes the binary up to several Gyr to merge (Belczynski et al., 2002; Belczynski et al., 2018; Safarzadeh and Berger, 2019). Finally, supernovae have not been found within short GRB localizations to deep limits (Kann et al., 2011).

The first unambiguous connection between a short GRB and its progenitor occurred on August 17, 2017 at 12:41:04 UTC (Abbott et al., 2017a). The Advanced Laser Interferometer Gravitational-wave Observatory (LIGO; Aasi et al. 2015) de-
ected the BNS merger GW170817 (Abbott et al., 2017c, 2019b), and approximately 1.7 s later, the Fermi Gamma-ray Burst Monitor (GBM; Meegan et al. 2009) and the INTEGRAL SPI-ACS detected the spatially-consistent GRB 170817A (Goldstein et al., 2017; Savchenko et al., 2017).\(^2\) The joint detection is shown in Figure 1.6. Initial reports sparked world-wide follow-up in all messengers and wavelengths, leading to the discovery of the kilonova AT2017gfo within 11 hours and the identification of the host galaxy NGC 4993 (Abbott et al., 2017a). The myriad of observations generated an unprecedented amount of science from one event: confirmation of NS mergers as progenitors of short GRBs, a precise measurement of the speed of gravity (Abbott et al., 2017a), an independent constraint on the Hubble constant (Abbott et al., 2017), the first unambiguous detection of a kilonova (e.g., Covino et al. 2017; Cowperthwaite et al. 2017; Nicholl et al. 2017; Smartt et al. 2017; Soares-Santos et al. 2017), and the first direct evidence of r-process nucleosynthesis in the Universe (e.g., Abbott et al. 2017b; Chornock et al. 2017; Pian et al. 2017; Tanvir et al. 2017).

GRB 170817A initially appeared as a standard, weak short GRB (Goldstein et al., 2017). However, given the distance to NGC 4993, GRB 170817A is found to have a luminosity of $\sim 10^{46}$ ergs – orders of magnitude lower than any other GRB with known redshift (Abbott et al., 2017a). Furthermore, the afterglow was not detected until $\sim 9$ days later, when rising X-ray emission was observed by the Chandra X-ray Observatory (Margutti et al., 2017) and a detection in radio shortly afterwards (Alexander et al., 2017). Given the low luminosity of the GRB and late-

\(^2\)Due to noise in the aLIGO Livingston detector (Pankow et al., 2018), the reporting of GW170817 was slightly delayed. So although the GW signal arrived first, GRB 170817A was in fact reported before GW170817.
Figure 1.6: Multi-messenger detection of GW170817 and GRB 170817A. **Top:** Fermi/GBM lightcurve summed over 3 detectors (10-50 keV) for GRB 170817A. **Second:** Same as above but summed over 50-300 keV. **Third:** INTEGRAL/SPI-ACS lightcurve summed between ∼100 keV-80 MeV. **Bottom:** GW time-frequency plot of GW170817 combining data from LIGO-Hanford and LIGO-Livingston.

time afterglow detection, the jet could be modelled as a normal short GRB viewed a relatively large angle with respect to the jet axis (i.e., $\theta_e \sim 20^\circ - 40^\circ$) (Alexander et al., 2017; Margutti et al., 2017). This is supported by radio detections of superluminal
motion of the afterglow, which constrained the viewing angle to $\sim 20$ deg from the jet axis and the initial Lorentz factor $\Gamma > 4$ (Mooley et al., 2018a,b).

Since GW170817, the GW interferometer network has expanded to include the Japanese interferometer Kamioka Gravitational Wave Detector (KAGRA; Akutsu et al. 2019) and has robustly detected 4 additional NS mergers: BNS GW190425 (Abbott et al., 2020a) and NSBHs GW200105 and GW200115 (Abbott et al., 2021c) and GW191219_163120 (Abbott et al., 2021e). LIGO, Virgo, and KAGRA (LVK) have also detected a few uncertain NSBHs: GW190814 (Abbott et al., 2020c) whose secondary mass of $\sim 2.6 M_\odot$ makes it either the the lightest BH or the heaviest NS known and GW200210_092254 whose secondary mass also lies within the mass gap at $2.83 M_\odot$ (Abbott et al., 2021e).

As exciting as these new detections of NS mergers have been, none other than GW170817 have associated EM emission despite dedicated multi-wavelength campaigns (e.g., Anand et al. 2021; Antier et al. 2020; Becerra et al. 2021; Chang et al. 2021; Dobie et al. 2019; Gompertz et al. 2020; Hosseinzadeh et al. 2019; Kasliwal et al. 2020; Kim et al. 2021; Page et al. 2020; Paterson et al. 2021; Pozanenko et al. 2019; Sasada et al. 2021; Fletcher et al., in prep). This low joint detection rate is in line with expectations (Howell et al., 2019). BNS merger production of GRBs may be intrinsically low. Observational factors could affect also observed rates, such as the difficulty for optical telescopes to survey the often large ($> 200$ deg$^2$) GW localizations (Petrov et al., 2022) as well as the challenges in detecting weak emission from nearby GRBs (e.g., GRB 170817A would have only been detected out to $\sim 75$
Mpc by the GBM (Goldstein et al., 2017) and \( \sim 100 \) Mpc by Swift (DeLaunay and Tohuvavohu, 2021)).

Joint detection rates are expected to grow in future observing runs as the distance to which upgraded GW observatories are sensitive increases (Abbott et al., 2020b). Future GW/GRB detections will also enable population studies of NS mergers, where the distributions of progenitor properties (e.g., masses, spins, inclination angles) can be related to the range of properties seen in short GRBs. They will also inform the highly uncertain NS equation of state (EOS). Along with the total mass of the binary, the EOS dictates the type of remnant left behind after merger (Margalit and Metzger, 2019). Combinations of binary mass and remnant type lead to different predictions for the EM signature, including the presence of a relativistic jet and kilonova properties (e.g., luminosity, color, and kinetic energy). Detecting EM emission from NS mergers will test these predictions and help define the mass transitions between remnant types. It has been estimated that \( \sim 10 \) detections of BNS mergers are needed to constrain the maximum mass of a non-spinning NS, \( M_{\text{TOV}} \), to within a few percent precision (Margalit and Metzger, 2019). Multi-messenger detections will also place constraints on GRB jet structure (Hayes et al., 2020), apply further tests of General Relativity (Abbott et al., 2017a), and constrain astrophysical rates of NS and BH formation.

1.4 Current Issues With GRB Classification

Although Type Ic SNe and BNS mergers have been linked to long and short GRBs, respectively, the idea that all long GRBs result from collapsars and all short
GRBs result from mergers is over-simplified. Only a small fraction (< 5%) of GRBs have a direct progenitor association, largely due to observational biases. At early times, afterglows from collapsar GRBs outshine the SNe, and follow-up instruments must perform lengthy monitoring of the GRB position to detect the SN, which is not always feasible. That said, some long GRBs have deep follow-up observations but no reported SN counterparts (Kann et al., 2011). For short GRBs, GW detectors are necessary to make GRB-merger associations, and joint detections were not achievable until 2015 when GW astronomy became possible with LIGO and Virgo (Abbott et al., 2016b). Future associations are also highly dependent on the observing schedules of GW instruments (e.g., Howell et al. 2019).

Due to the paucity of progenitor associations, GRBs are generally classified by the $T_{90}$ division at 2 s. However, the minimum and maximum durations of GRBs from collapsars and mergers are unknown (Zhang, 2019), and there is significant overlap between the long and short $T_{90}$ distributions (Figure 1.4). $T_{90}$ measurements are also affected by multiple factors. Cosmological dilation will stretch the intrinsic GRB duration, and as the gamma-ray emission travels through space, it also spreads – ultimately weakening the observable flux and leading to a shorter $T_{90}$ (Kocevski and Petrosian, 2013). The $T_{90}$ distribution is also detector-dependent, and the split between long and short GRBs varies with respect to instrument bandpass (Bromberg et al., 2013; Qin et al., 2012). The $T_{90}$ distribution is also influenced by GRBs that do not clearly fit in either class, such as short GRBs with extended emission. Short GRBs with extended emission display initial short, hard spikes but are followed by long, low-energy tails (Norris and Bonnell, 2006). The mechanism for producing
extended emission is currently unknown, although magnetars and NSBH mergers are leading candidates (Desai et al., 2019; Metzger et al., 2008).

There are also examples of cross-contamination between long and short populations (Bromberg et al., 2013). GRB 200826A with $T_{90} = 1.1$ s has been connected to a SN, making it the shortest known GRB with a collapsar origin (Ahumada et al., 2021). The short duration is likely due to an intrinsically short period of central engine activity or an unusually dense stellar envelope in which most of the jet remained cocooned. On the other hand, GRB 211211A is a long GRB ($T_{90} > 30$ s) with a claimed kilonova association (Rastinejad et al., 2022; Yang et al., 2022). Kilonovae are connected to BNS mergers, but the diversity of conditions leading to their production is still not well understood. It has been suggested that collapsars with very massive ($> 130 M_\odot$) envelopes could produce kilonovae (Siegel et al., 2021). If GRB 211211A was in fact formed by a BNS merger, it redefines the classical notion of what a short GRB is. GRB 211211A also raises questions for other nearby long GRBs for which no SN counterpart was observed, such as GRB 060505 (Fynbo et al., 2006), GRB 060614 (Gehrels et al., 2006), and GRB 211227A (Lü et al., 2022). In fact, GRB 060614 shares similar features to GRB 211211A such as lightcurve morphology, close distance ($< 500$ Mpc), and a claimed kilonova counterpart (Yang et al., 2015).

Therefore, classification by $T_{90}$ alone is inadequate. Other observational properties such as hardness ratio, spectrum, spectral lag, host galaxy type, and host galaxy offset are also used (when available) to classify GRBs (Zhang et al., 2009). Yet, as with $T_{90}$, the division of these properties between collapsar and merger GRBs can be
vague. There are many questions that remain about the relationship between GRBs and their progenitors.
CHAPTER 2

PHYSICS AND INTRINSIC PROPERTIES OF GRBS

GRBs are complex, transient phenomena, and much is still unknown about how they are produced and what their intrinsic properties are. This chapter summarizes the standard emission mechanisms evoked to explain GRBs and outlines what is currently known about the GRB luminosity function and rate density. Specifically, Section 2.1 details prompt and afterglow emission, while Section 2.2 introduces the GRB luminosity function and rate density and discusses the challenges faced when describing these distributions.

2.1 The Physics of GRBs

Regardless of progenitor, the physics of GRB jets is thought to be similar (Figure 2.1). A recently-formed black hole (Narayan et al., 1992; Woosley, 1993) or magnetar (Usov, 1992) ejects a large amount of energy into a small volume, powering a collimated relativistic outflow (Goodman, 1986; Paczynski, 1986; Piran, 1999). At small radii, the density of the outflow is high and the emission is optically thick. The outflow expands, becomes optically thin, and releases energy in the form of thermal radiation at the photosphere (i.e., the physical photosphere of a progenitor star or
leftover debris from a compact binary merger). Additional energy is released through processes internal to the jet, such as colliding shock fronts (Rees and Meszaros, 1994) and/or magnetic dissipation sites (Lyutikov and Blandford, 2003; McKinney and Uzdensky, 2012; Zhang and Yan, 2011). The internal dissipation is what gives rise to the non-thermal radiation observed as GRB prompt emission. As the jet extends further outward and interacts with the circumburst medium, the multi-wavelength afterglow component forms and is well-described by synchrotron shock models (Sari et al., 1998).

2.1.1 Prompt Emission

Prompt emission is the earliest electromagnetic signal of GRBs and can be loosely defined as the initial emission observed within the keV-MeV range. Prompt emission has also been detected at optical, X-ray, and high-energy gamma-ray wavelengths, but it is currently unclear whether this is a common feature of all GRBs or unique to only a subset. In fact, despite over 50 years of observations, the mechanisms
of GRB prompt emission even at keV-MeV energies are still not well understood. Open questions surround how GRB jets are formed, whether they are dominated by matter or Poynting flux, how energy within the jets is dissipated, and how the photons are radiated. The challenge in answering these questions stems from the fact that GRBs display such temporal and spectral diversity that, to date, no theoretical model has been able to explain all observed properties – hinting that a complex combination of processes is likely involved.

2.1.1.1 The Fireball Model and Internal Shocks

The most commonly accepted explanation for the origin of the GRB outflow is the fireball model (Kobayashi et al., 1999; Meszaros and Rees, 1993; Piran et al., 1993). In this framework, the fireball is an expanding, isotropic photon-pair outflow with a small fraction of baryons and whose initial energy is much larger than its rest mass. Magnetization within the jet is considered negligible, and the dynamics can be explained with relativistic hydrodynamics alone. The dynamical evolution of the fireball constitutes three phases: (1) acceleration, (2) coasting, and (3) deceleration. At early times, while the fireball is dominated by leptons, it expands with Lorentz factor $\Gamma$ proportional to the radius from the central engine, $R$. After the fireball is dominated by baryons and becomes optically-thin, $\Gamma$ peaks at its maximum value and the jet coasts with approximately constant $\Gamma$. The deceleration phase begins once the jet begins significant interactions with the circumburst medium.

Within the fireball model, one of the leading mechanisms for internal energy dissipation is collisionless internal shocks (Rees and Meszaros, 1994). In this scenario,
the entire jet moves with an average bulk Lorentz factor but is comprised of many shells moving at different Lorentz factors, either due to intermittent central engine activity or intrinsic inhomogeneity of the outflow. Faster trailing shells collide with slower forward shells and produce shock fronts at which particles are accelerated and subsequently radiate via synchrotron, inverse Compton scattering, and/or other non-thermal mechanisms.

Internal shocks were proposed to alleviate theoretical problems when introducing baryons to a pure photon-pair fireball. A baryon population of just $\geq 10^{-5}$ of the total jet causes increased bulk kinetic energy of the fireball at the expense of radiation losses (Cavallo and Rees, 1978; Shemi and Piran, 1990). Internal shocks can convert the kinetic energy back into radiation at shock collision sites. They also naturally explain the multiple pulses and rapid variability in GRB lightcurves; however, internal shock models predict efficiencies to gamma-ray production of only a few percent (Kumar, 1999; Panaitescu et al., 1999), while observational constraints have been made ranging from $\sim 1$–90% (Beniamini et al., 2015; Fong et al., 2015; Nava et al., 2014; Racusin et al., 2011; Wang et al., 2015). Therefore, internal shocks can only account for low-efficiency GRBs.

Alternative models invoking magnetic dissipation of the outflow predict higher efficiencies (e.g., Zhang and Yan 2011) and can produce basic features of GRB lightcurves and spectra (Zhang and Zhang, 2014). Polarization measurements would be helpful in constraining the degree of magnetization within the jet, as well as the radiation mechanisms involved (Toma et al., 2009). There have been a few claims of linear polarization in GRBs (e.g., Coburn and Boggs 2003; Kole et al. 2020; Willis
et al. 2005; Yonetoku et al. 2011), but the detections are either low-significance or do not agree with previous reports.

A complete description of GRB prompt emission likely includes a combination of matter-dominated and magnetically-dominated components such that the observed features are shaped by properties of the progenitor and the central engine (Gao and Zhang, 2015; Mészáros and Rees, 1997; Vlahakis and Konigl, 2003).

### 2.1.1.2 GRB Spectra and Radiation Models

Spectral observations provide some of the most important diagnostics for GRB prompt emission models, and since the launch of Fermi in 2008, the understanding of GRB spectra has dramatically expanded. With its two instruments, the GBM and the Large Area Telescope (LAT; Atwood et al. 2009), Fermi is sensitive to a wide energy range from 8 keV to 300 GeV and detects ~240 GRBs per year, providing an unprecedented number of spectra (von Kienlin et al., 2020). Currently, three major spectral features have been identified in GRB prompt emission: (1) a main non-thermal component, (2) a typically sub-dominant thermal component, and (3) a delayed high-energy tail (Figure 2.3).

The non-thermal component is the dominant feature in most GRB spectra, and for bright GRBs, is often best fit by the phenomenological Band function (Band et al., 1993):

\[
N(E) = A \begin{cases} 
E^\alpha \exp[-E/E_0] & (\alpha - \beta)E_0 > E \\
[ (\alpha - \beta)E_0 ]^{\alpha-\beta} \exp[(\alpha - \beta)] E^\beta & (\alpha - \beta)E_0 < E 
\end{cases}
\]  
(2.1)
where $\alpha$ is the low energy index, $\beta$ is the high energy index, and $E_0$ is the break energy. The peak energy of the $\nu F \nu$ spectrum, $E_p$, is related to $E_0$ by $E_p = (2 + \alpha)E_0$. The $E_p$ distribution spans several orders of magnitude from a few keV up to several MeV, while generally $\alpha \sim -1$ and $\beta \sim -2$. In GRBs with low fluence or that have been observed by instruments with narrow bandpass, the non-thermal component is often best fit by a single power law (PL) or a cutoff power law (CPL):

$$N(E) = A \left( \frac{E}{100 \text{ keV}} \right)^\alpha \exp \left( \frac{E}{E_c} \right) \quad (2.2)$$

where $E_c$ is the cutoff energy and $E_p = (2 + \alpha)E_c$. Broadband observations have shown that, in many cases, spectra are best-fit with the CPL (PL) function when $\beta (E_p)$ cannot be constrained by the instrument.

It is an ongoing effort to relate GRB spectra to physical radiation mechanisms. Synchrotron radiation is predicted in almost all prompt emission models and is produced when charged particles are deflected by a magnetic field. For GRBs, this could occur as electrons are accelerated at shock fronts or by magnetic reconnection sites within the jet. The emission power radiated via synchrotron from a single electron in a random magnetic field is

$$P(\gamma_e) = \frac{4}{3} \sigma_T c \gamma_e^2 \beta_v^2 U_B \quad (2.3)$$

where $\beta_v$ is the electron velocity averaged over pitch angle and $U_B$ is the magnetic field energy density. Assume a relativistic shock that accelerates a continuously-injected population of electrons to a power law distribution of Lorentz factor with spectral

\footnote{In the GRB community, the CPL function is also known as the “Comptonized model.”}
Figure 2.2: GRB synchrotron spectrum from Sari et al. (1998) for a population of electrons accelerated by a relativistic shock. **Top:** The fast-cooling regime. The temporal scalings above the arrows correspond to adiabatic evolution, while the scalings below correspond to radiative evolution. **Bottom:** The slow cooling regime.

The spectrum is characterized by a multi-segment broken power law with break frequencies $\nu_m$, $\nu_c$, and $\nu_a$, where $\nu_m$ is the characteristic frequency corresponding to the minimum Lorentz factor of the injected electron distribution, $\nu_c$ is the cooling frequency, and $\nu_a$ is the synchrotron self-absorption frequency (Figure 2.2).
During the prompt emission, electrons are thought to be in the fast-cooling regime (i.e., $\nu_c < \nu_m$), in which the electrons are cooled almost immediately after injection (Ghisellini et al., 2000). In the fast-cooling regime, the low energy photon index $\alpha$ is expected to be -1.5 (Piran, 1999); this is steeper than observed in many GRBs (Poolakkil et al., 2021). If models allow for slow-heating synchrotron, $\alpha$ should be no steeper than -2/3. This is known as the synchrotron “line-of-death” and is also violated by a significant fraction of GRBs (Preece et al., 1998). Furthermore, if GRBs are indeed in the fast-cooling regime, synchrotron from internal shocks can only produce an $E_p$ of a couple keV (Zhang, 2018). Therefore, synchrotron shock radiation cannot explain all GRB spectra (though see, e.g., Beniamini and Piran 2013; Burgess et al. 2020).

The second feature seen in GRB spectra is a thermal contribution. A number of GRBs are best fit with a Band function plus a blackbody with temperature of order 10 keV (Axelsson et al., 2012; Guiriec et al., 2011, 2013). Although typically sub-dominant, thermal components have been found to dominate the spectra of a handful of GRBs, such as GRB 090902A (Pe’er et al., 2012; Ryde et al., 2010). Thermal emission is expected within the fireball model, arising from breakout at the photospheric radius (Meszaros and Rees, 2000). Thermalized photons are also needed in the internal shock model to drive the conversion from radiative energy to kinetic energy in the fireball and form collisionless shocks. Meszaros and Rees (2000) has also shown that in the fireball + internal shock model the thermal component should be brighter than observed and potentially dominate the non-thermal synchrotron emis-
Figure 2.3: Time-resolved model spectra of GRB 190114C from Ajello et al. (2020) using LAT and GBM data. **Left:** At early times, GRB 190114C is best-fit with a Band+blackbody model (blue) and then a CPL+PL model (green). **Right:** A second turnover appears is best-fit with CPL+CPL (red) and then Band+CPL (cyan). The second turnover disappears, and the observed emission is best-fit by a CPL+PL (magenta).

- unless another mechanism is available to suppress the photospheric emission, such as a magnetized central engine (Gao and Zhang, 2015; Veres et al., 2012).

The third component seen in GRB spectra is the high-energy tail. It extends to $>100$ MeV and is occasionally observed to reach down into the X-ray band. It has been discovered in the spectra of only a few bright GRBs and is also typically delayed by a few seconds with respect to the keV-MeV emission. The first clear detections of the high-energy tail were made by *Fermi*-LAT in GRB 081024B (Abdo et al., 2010), GRB 090510 (Ackermann et al., 2010), GRB 090902B (Abdo et al., 2009), and GRB 090926A (Ackermann et al., 2011). In GRB 090926A, a spectral break was also detected at around 1.4 GeV – the first observation of a second turnover in GRB spectra. The origin of the high-energy component is not yet well understood, though many studies have found it consistent with early onset of afterglow emission.
In such a scenario, the emission could potentially arise from inverse-Compton scattering of prompt photons by electrons accelerated in the forward shock. The second turnover may result from absorption due to pair-production at high energies (Ajello et al., 2020).

### 2.1.2 Afterglow Emission

Afterglow emission in GRBs is broadband radiation caused by the forward shock of the jet colliding with the external circumburst medium (Sari et al., 1998). It is longer-lived than the prompt emission and can be observed up to several years after the initial burst (e.g., GRB 170817A; Hajela et al. 2021). Unlike prompt emission, the afterglow is relatively well-understood and described by synchrotron shock radiation (Figure 2.2). There are, however, many variations of afterglow models depending on the assumed density of the surrounding environment, whether or not there is continual energy injection, the structure of the jet, etc (Chevalier and Li, 2000; Meszaros et al., 1998; Sari et al., 1998). The afterglow flux is conventionally described as $F_\nu \propto t^{-\alpha} \nu^{-\beta}$, where $\alpha$ and $\beta$ are the temporal and spectral indices, respectively. Assuming certain conditions about the environment and the external shock, relationships between these indices in different regimes can be described a set of closure relations, which are used to test afterglow models against the data. Although not discussed here, closure relations can be found in, e.g., Chevalier and Li (2000); Gao et al. (2013); Sari et al. (1998); Zhang et al. (2006) and Ryan et al. (2020).
The afterglow is most frequently detected in X-rays, due to its brightness and typically rapid onset (Lien et al., 2016). The canonical X-ray lightcurve consists of 5 components: (1) an initial steep decay, (2) a plateau, (3) a normal decay phase, (4) a jet break, and (5) X-ray flares. The initial decay is the first part of the afterglow and falls with a temporal slope of $\lesssim -3$ (Zhang, 2018). It is thought to be related to the transition between prompt and afterglow emission (i.e., the time during which the central engine stops and the forward shock has accumulated enough material to radiate brightly). The next decay phase has a typical slope greater than $-1$, and is called a plateau if it is close to 0 (Zhang, 2018). The change in slope is interpreted as the result of continuous energy injection into the external shock, possibly from long-lived central engine activity or intrinsic inhomogeneity of the jet. The normal decay phase has a slope of $\sim -1$ and is the conventional value expected from the external forward shock (Zhang, 2018). This slope can steepen after the jet break, which is a geometrical effect that occurs when the decelerating jet becomes wider than $\Gamma^{-1}$ and the observed flux drops rapidly at all wavelengths (Section 1.2). For a top-hat jet propagating into a medium of constant density, the jet opening angle $\theta_j$ can be derived from the jet break time $t_j$ (Frail et al., 2001):

$$\theta_j = 0.057 \left( \frac{t_j}{\text{1 day}} \right)^{3/8} \left( \frac{1 + z}{2} \right)^{-3/8} \left( \frac{E_{\text{iso}}}{10^{53} \text{ erg}} \right)^{-1/8} \left( \frac{n_\gamma}{0.2} \right)^{1/8} \left( \frac{n}{0.1 \text{ cm}^{-3}} \right)^{1/8}$$

where $E_{\text{iso}}$ is the observed isotropic-equivalent gamma-ray energy, $n_\gamma$ is the efficiency of converting kinetic energy into gamma-rays, and $n$ is particle number density of the external medium. Finally, flares are abrupt re-brightening episodes that appear in
many X-ray afterglows (Falcone et al., 2007). They are spectrally harder and thought to be of separate origin than the underlying emission. This is because the temporal slope of the underlying emission does not change after the flare. In fact, flares are thought to be related to brief reactivation periods of the central engine (Falcone et al., 2007; Kocevski et al., 2007; Margutti et al., 2010).

While most optical afterglows show similar behavior to their X-ray counterparts, around \(\sim 40\%\) of optical afterglows show different temporal slopes and decays (Panaitescu and Vestrand, 2011). This could be due to evolution of the synchrotron spectrum, lateral expansion of only a fraction of the jet, or multiple emission sites (e.g., Wang et al. 2015). Another feature is that \(\gtrsim 30\%\) of detected afterglows show a lack of optical emission from that expected from the fireball model. These are known as \textit{optically dark} afterglows, and the designation is determined from the ratio of X-ray flux to optical flux, although the exact ratio can vary according to the study (Jakobsson et al., 2004; Pedersen et al., 2006; van der Horst et al., 2009). The optical emission is mostly likely missed because of an intrinsic low luminosity, extinction in dusty host galaxies or, for high-\(z\) GRBs, Lyman-\(\alpha\) absorption from the intergalactic medium (IGM). Optically-dark afterglows are occasionally detected in radio (e.g., Schroeder et al. 2022). Radio afterglows tend to fade on slower timescales than observed in X-rays and optical, and they exhibit a peak at the characteristic synchrotron frequency \(\nu_m\) or the synchrotron self-absorption frequency \(\nu_a\) (Chandra and Frail, 2012).

Afterglows are also detected at high (>MeV) energies. As mentioned in Section 2.1.1.2, \textit{Fermi-LAT} observations have provided an extensive study of afterglows,
with $\sim 17$ detections of GeV emission from GRBs per year (Ajello et al., 2019). GeV afterglows are generally observed as simple power laws, delayed with respect to the MeV emission and lasting $\gtrsim 10^3 - 10^4$ seconds (Ackermann et al., 2013).

One of the most exciting discoveries in the last 5 years is the detection of TeV photons from a GRB. On January 14, 2019, GRB 190114C triggered the Swift (Gropp et al., 2019) and Fermi satellites (Ajello et al., 2019; Hamburg et al., 2019; Kocevski et al., 2019), and approximately 1 minute later, was detected by the the MAGIC Cherenkov telescopes in the 0.2-1 TeV energy range with a significance of $> 50\sigma$ (Acciari et al., 2019). The TeV emission lasted over 2000 seconds, and correcting for extinction from extragalactic background light (EBL), was best-fit with a power law of slope $\sim -2.2$ (Acciari et al., 2019). This observation was the first clear violation of the maximum synchrotron energy in GRBs. The maximum synchrotron energy is the highest energy of photons that electrons can radiate when gyrating around magnetic fields lines. It can be found by equating the synchrotron cooling timescale to the Larmor timescale and is roughly $\sim 7\Gamma(1 + z)^{-1}$ GeV (Gill and Granot, 2022). Therefore, the TeV photons from GRB 190114C provided new insight into GRB radiation physics – a mechanism other than synchrotron radiation is required to explain the late-time afterglow. The TeV emission could be explained as inverse scattering of low-energy photons in the un-shocked medium, synchrotron self-Compton scattering (SSC), where photons created by the synchrotron electrons up-scatter off the same electron population, or hadronic rather than leptonic processes (Acciari et al., 2021; Ajello et al., 2019). Since GRB 190114C, there have been more reports of TeV emission in the afterglow: GRB 160821B (Acciari et al., 2021), GRB 180720B (Abdalla

37
et al., 2019), GRB 190829A (Abdalla et al., 2021), and GRB 201216C (Fukami et al., 2021). TeV photons are only expected to be seen from nearby GRBs since they pair produce with EBL photons at $z \gtrsim 0.1$ (Gill and Granot, 2022).

Afterglows carry a wealth of information due to their multi-chromatic nature. In addition to constraining models of GRB emission, detections of afterglows can also lead to host galaxy associations and redshifts (Section 1.1, which are essential for measuring the rest-frame properties of GRBs.

2.2 Intrinsic Properties

The intrinsic properties of GRBs are hidden from the observer due to their extragalactic origin. Cosmological expansion of the universe shifts the energies, durations, and rates of GRBs, and without distance measurements, their rest-frame properties remain unknown. As exemplified in Chapter 1, knowledge of true GRB energetics has important implications for their emission processes and progenitor types. These implications can be further extended to inform the end stages of massive stars, the creation of neutron stars and black holes, and the cosmic evolution of both GRB progenitors and their hosts.

2.2.1 GRB Redshift Distribution

The distance of a GRB can be found most directly by measuring its redshift, $z$, which is an increase in the observed wavelength of a photon relative to its emitted wavelength. Redshift resulting from cosmological expansion is related to luminosity
distance, \( D_L \), via

\[
D_L = (1 + z)D_M = (1 + z)\frac{c}{H_0} \int_0^z \frac{dz}{\sqrt{\Omega_m(1 + z)^3 + \Omega_\Lambda}}
\]

where \( D_M \) is the co-moving distance and \( H_0 \) is the Hubble constant. The parameters \( \Omega_M \) and \( \Omega_\Lambda \) are normalized dimensionless numbers quantifying how the present energy density of the Universe is divided. More specifically, \( \Omega_M \) is the fraction of matter density (baryonic plus dark) and \( \Omega_\Lambda \) is the density associated with dark energy (Hogg, 1999).

There are three methods by which the redshift of a GRB can be measured: (1) detection of absorption lines in the afterglow, (2) detection of emission lines from the host galaxy, and (3) photometric comparison of a specific spectral feature (typically the Lyman-\( \alpha \) break) in different filters. Redshifts from host galaxies, particularly \( z < 1 \), can be more suspect than those from afterglows, since the probability of chance coincidence between a GRB and a random galaxy is higher at nearby distances (Fong et al., 2022; Howell et al., 2014). Photometric redshifts are the least robust, since a particular photon spectrum must be assumed, as well as estimates of the amount of extinction along the line-of-sight (Krühler et al., 2011).

The GRB redshift distribution, \( R(z) \), is the observed rate of GRBs as a function of redshift and is given in units of number per solid angle \((d\Omega)\) per redshift interval \((dz)\) per time interval in the observer frame \((dt_{\text{obs}})\). This distribution can be derived from the product of the true rate density, \( R_{\text{GRB}}(z) \) (described in Section 2.2.2)
Figure 2.4: The GBM redshift (left) and luminosity (right) distributions from Poolakkil et al. (2021), spanning July 2008–June 2018.

and the co-moving volume element, $dV/dzd\Omega$:

$$R(z) = R_{GRB}(z) \frac{dVd\Omega d_{\text{src}}}{dzd\Omega_{\text{obs}}} = R_{GRB}(z) \frac{dV}{(1 + z) \ dzd\Omega} \tag{2.6}$$

where

$$\frac{dV}{dzd\Omega} = \frac{4\pi c \ D_L^2}{H_0 \ (1 + z)^2 \ \sqrt{\Omega_M (1 + z)^3 + \Omega_\Lambda}} \tag{2.7}$$

and a flat space-time has been assumed.

Observationally, the redshift distribution is plagued by selection effects. Only $\sim 30\%$ of Swift GRBs and $\sim 5\%$ of Fermi\textsuperscript{2} GRBs have redshift measurements and their distributions (Figure 2.4) suffer from inherent and instrumental biases. Inherent biases include the Malmquist bias, the so-called redshift desert, and host galaxy

\textsuperscript{2}Redshifts for GBM GRBs between June 2008–June 2018 can be found in the GBM spectral catalog (Poolakkil et al., 2021). For a list of GBM GRB redshifts from July 2018–Present, see Table 2.1.
extinction (Howell et al., 2014). The Malmquist bias describes the preferential detection of nearby and highly-luminous objects (Malmquist, 1922). The redshift distribution is thus flux-limited: spectra from intrinsically low-luminous afterglows and high-$z$ galaxies are less likely to be detected. The redshift desert is the interval $(1.2 \lesssim z \lesssim 3)$ in which the characteristic spectral lines used to measure redshift are difficult to detect (Steidel et al., 2004). Emission lines have dropped into the infrared (IR) and the strong absorption lines in the afterglow are still in the ultraviolet (UV). It is in this region that photometric redshifts can be most helpful (Nugent et al., 2022). As mentioned in Section 2.1.2, host galaxy extinction also effects the detection of optical afterglows, skewing the redshift distribution towards GRBs in less dusty environments.

Instrumental biases primarily concern GRB localization areas. X-ray and optical afterglows can fade rapidly (Kann et al., 2011; Racusin et al., 2011), and from the first reports of a GRB, follow-up telescopes race to re-point and tile the localization area for the afterglow. Gamma-ray instruments that localize using relative signals in multiple scintillation detectors, such as Fermi GBM, have localization errors on the order of degrees (Goldstein et al., 2020), which is challenging for most optical telescopes to scan efficiently (e.g., Singer et al. 2015). However, new wide-field optical surveys like ZTF (Bellm et al., 2019) have demonstrated the capability to rapidly scan GBM localizations and detect afterglows (Coughlin et al., 2019). Though having a lower detection rate than GBM, the Swift satellite routinely localizes GRBs with $\sim$arc-min accuracy and has recently improved GRB follow-up with its GUANO-NITRATES pipeline, yielding $\sim$ 13 additional arcminute localizations of GRBs per
year (DeLaunay and Tohuvavohu, 2021; Tohuvavohu et al., 2020). Instruments, like the X-shooter on the Very Large Telescope (Vernet et al., 2011) with a spectrometer extending into the NIR and UV bands have also come online. Optical telescopes are still subject to observational biases (e.g., Galactic extinction, angular distance from the Sun, source declination, etc.), but given recent improvements in technology, redshifts are being detected at a faster cadence.

2.2.2 GRB Rate Density

The GRB rate density, $R_{GRB}(z)$, describes the volumetric formation rate of GRBs as a function of redshift and is shaped by the evolution of their progenitors, the environments in which they are created, and the physical conditions that determine successful jet production. GRBs have at least two different progenitors (i.e., collapsars and BNS mergers) and therefore at least two different rate densities. The difference between the progenitor rate and the corresponding GRB rate yields the progenitors’ efficiency to GRB production.

2.2.2.1 Collapsar GRBs

Due to the short lifespans ($\sim 30$ Myr) of massive stars, the formation rate of GRBs with collapsar origin is often assumed to be proportional to the cosmic star formation rate (Hopkins and Beacom, 2006; Madau and Dickinson, 2014; Madau and Fragos, 2017):

$$R_{GRB}(z) = \rho_0 \frac{SFR(z)}{SFR(0)}$$  \hspace{1cm} (2.8)
Table 2.1: GBM GRBs with redshifts from July 2018–Present. GRBs with asterisks did not trigger GBM but were recovered in subthreshold searches; their $T_{90}$ durations are taken from BAT observations. Redshift type is classified as ‘S’ for spectral detection of absorption lines in the afterglow, ‘E’ for detection of emission lines, ‘HG’ for redshifts taken from the host galaxy, and ‘P’ for photometric. Redshifts for GBM GRBs before June 2018 can be found in the GBM spectral catalog (Poolakkil et al., 2021)

<table>
<thead>
<tr>
<th>GRB</th>
<th>$T_{90}$ (s)</th>
<th>Redshift</th>
<th>Type</th>
<th>GCN Ref. Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>180720B</td>
<td>48.90</td>
<td>0.654</td>
<td>S</td>
<td>22996</td>
</tr>
<tr>
<td>180728A</td>
<td>6.40</td>
<td>0.117</td>
<td>S</td>
<td>23055</td>
</tr>
<tr>
<td>181010A</td>
<td>9.73</td>
<td>1.39</td>
<td>S</td>
<td>23315</td>
</tr>
<tr>
<td>181020A</td>
<td>15.10</td>
<td>2.938</td>
<td>S</td>
<td>23356</td>
</tr>
<tr>
<td>190114C</td>
<td>116.35</td>
<td>0.42</td>
<td>S</td>
<td>23695, 23708, 23710</td>
</tr>
<tr>
<td>190324A</td>
<td>26.88</td>
<td>1.1715</td>
<td>S</td>
<td>23999</td>
</tr>
<tr>
<td>190719C</td>
<td>175.6</td>
<td>2.469</td>
<td>HG</td>
<td>25252</td>
</tr>
<tr>
<td>190829A</td>
<td>59.39</td>
<td>0.078</td>
<td>S</td>
<td>25565, 25595</td>
</tr>
<tr>
<td>191011A</td>
<td>25.08</td>
<td>1.722</td>
<td>S</td>
<td>25991</td>
</tr>
<tr>
<td>200524A</td>
<td>37.76</td>
<td>1.256</td>
<td>S</td>
<td>29673</td>
</tr>
<tr>
<td>200613A</td>
<td>478.0</td>
<td>1.22</td>
<td>HG</td>
<td>29320</td>
</tr>
<tr>
<td>200826A</td>
<td>1.13</td>
<td>0.7481</td>
<td>S</td>
<td>28319</td>
</tr>
<tr>
<td>200829A</td>
<td>6.91</td>
<td>1.25</td>
<td>P</td>
<td>28338</td>
</tr>
<tr>
<td>201015A*</td>
<td>9.78</td>
<td>0.42</td>
<td>S</td>
<td>28649, 28661</td>
</tr>
<tr>
<td>201020A</td>
<td>21.5</td>
<td>2.903</td>
<td>S</td>
<td>28717</td>
</tr>
<tr>
<td>201020B</td>
<td>15.87</td>
<td>0.804</td>
<td>E</td>
<td>28765</td>
</tr>
<tr>
<td>201021C</td>
<td>35.33</td>
<td>1.070</td>
<td>S</td>
<td>28739</td>
</tr>
<tr>
<td>201216C</td>
<td>29.95</td>
<td>1.1</td>
<td>S</td>
<td>29077</td>
</tr>
<tr>
<td>201221A*</td>
<td>44.5</td>
<td>5.7</td>
<td>S</td>
<td>29100</td>
</tr>
<tr>
<td>201221D</td>
<td>0.14</td>
<td>1.046</td>
<td>S</td>
<td>29132</td>
</tr>
<tr>
<td>210204A</td>
<td>206.9</td>
<td>0.876</td>
<td>S</td>
<td>29432</td>
</tr>
<tr>
<td>210610A</td>
<td>8.19</td>
<td>3.5</td>
<td>S</td>
<td>30164, 30200</td>
</tr>
<tr>
<td>210610B</td>
<td>55.04</td>
<td>1.13</td>
<td>S</td>
<td>30182, 30194, 30201</td>
</tr>
<tr>
<td>210619B</td>
<td>54.79</td>
<td>1.937</td>
<td>S</td>
<td>30272</td>
</tr>
<tr>
<td>210722A</td>
<td>61.95</td>
<td>1.145</td>
<td>S</td>
<td>30487</td>
</tr>
<tr>
<td>210731A</td>
<td>25.85</td>
<td>1.2525</td>
<td>S</td>
<td>30583</td>
</tr>
<tr>
<td>210905A*</td>
<td>&gt; 30</td>
<td>6.318</td>
<td>S</td>
<td>30771</td>
</tr>
<tr>
<td>211023A</td>
<td>79.0</td>
<td>0.390</td>
<td>HG</td>
<td>31053</td>
</tr>
<tr>
<td>211207A*</td>
<td>3.73</td>
<td>2.272</td>
<td>S</td>
<td>31188</td>
</tr>
<tr>
<td>220101A</td>
<td>128.3</td>
<td>4.6</td>
<td>S</td>
<td>31353, 31359, 31363</td>
</tr>
<tr>
<td>220107A</td>
<td>33.02</td>
<td>1.246</td>
<td>S</td>
<td>31423</td>
</tr>
<tr>
<td>220117A*</td>
<td>49.81</td>
<td>4.961</td>
<td>S</td>
<td>31480</td>
</tr>
<tr>
<td>220521A</td>
<td>13.57</td>
<td>5.6</td>
<td>S</td>
<td>32079, 32099</td>
</tr>
<tr>
<td>220527A</td>
<td>10.50</td>
<td>0.857</td>
<td>S</td>
<td>32141, 32144</td>
</tr>
<tr>
<td>220627A</td>
<td>137.0</td>
<td>3.084</td>
<td>S</td>
<td>32291</td>
</tr>
</tbody>
</table>
Star formation rates and GRB rate as a function of redshift from Tanvir et al. (2021). The grey shaded region is obtained from UV observations reported in Madau and Fragos (2017), and the blue hatched region includes contributions from faint galaxies. The red points are from NIR observations GRB host galaxies, and the blue points are simulated expectations for the proposed THESEUS mission.

Figure 2.5: Star formation rates and GRB rate as a function of redshift from Tanvir et al. (2021). The grey shaded region is obtained from UV observations reported in Madau and Fragos (2017), and the blue hatched region includes contributions from faint galaxies. The red points are from NIR observations GRB host galaxies, and the blue points are simulated expectations for the proposed THESEUS mission.

where the rate has been normalized to the local \((z = 0)\) GRB rate, \(\rho_0\), with units of number per volume per year. Values for the local rate vary widely, though for long GRBs with luminosity \(L \geq 10^{50}\) ergs s\(^{-1}\), \(\rho_0 \sim 1\) Gpc\(^{-3}\) yr\(^{-1}\) (Ghirlanda and Salvaterra, 2022; Guetta et al., 2005; Howell et al., 2014; Lan et al., 2019; Lien et al., 2014; Pescalli et al., 2016; Petrosian et al., 2015; Wanderman and Piran, 2010). This is, in general, only valid for GRBs beamed toward the Earth. When taking into account the bipolar jet angle, the local rate density is increased by a beaming factor \(f_b^{-1}\) where \(f_b = 1 - \cos \theta_j \sim \theta_j^2/2\). For a median opening angle of 5.4° (Racusin et al., 2009), the beaming-corrected local rate is \(~225\) Gpc\(^{-3}\) yr\(^{-1}\).

There is evidence that long GRBs do not strictly follow the SFR, particularly at high redshifts where they appear to form in excess of SFR inferred by UV observations (Guetta and Piran, 2006; Li, 2008; Qin et al., 2010; Robertson and Ellis, 2011; Yüksel
et al., 2008). The high-$z$ excess (Figure 2.5) could be caused by metallicity evolution (Li, 2008; Yoon et al., 2006). Mass-loss from stellar winds scales with metallicity, and it is thought that low-metallicity ($\lesssim 0.3 \ Z_\odot$) stars retain enough mass and angular momentum to launch a jet (Woosley and Bloom, 2006; Woosley, 1993). Long GRBs are preferentially found in metal-poor environments, and since cosmic metallicities were lower in the early universe, this could explain the higher rate (Robertson and Ellis, 2011). The excess could also be explained by an evolving luminosity function stemming from changes to the initial mass function (Wang and Dai, 2011). Finally, the SFR is probed by various means, such as UV emission from young stars, IR from dust surrounding young stars, and radio which measures ionization in the ISM. These probes are also subject to selection effects, yielding poor constraints beyond $z = 4$ (Madau and Dickinson, 2014; Madau and Fragos, 2017), though new surveys targeting dusty and high-$z$ galaxies may find additional contributions to the SFR than previously known (see e.g., Dudzevičiūtė et al. 2020; Enia et al. 2022).

It is worth noting that some studies (e.g., Pescalli et al. 2015; Yu et al. 2015) find a low redshift ($z \lesssim 1$) excess in GRB rate as compared to the SFR. However, it has been shown that a low redshift excess can be obtained when using incomplete data samples (Pescalli et al., 2016). Furthermore, due to metallicity and/or luminosity evolution, only a small fraction of the local SFR is likely to produce GRBs.
Given the uncertainties in how the GRB rate compares to the SFR, it is also frequently modelled as a simple broken power law:

\[ R_{\text{GRB}}(z) = \rho_0 \begin{cases} 
(1 + z)^{\alpha_z}, & z < z_b \\
(1 + z_b)^{\alpha_z - \beta_z}(1 + z)^{\beta_z}, & z > z_b 
\end{cases} \]  

(2.9)

where \( \alpha_z \) is the low redshift index, \( \beta_z \) is the high redshift index, and \( z_b \) is the break. This form of the rate density follows the general trend of the SFR but allows for more flexibility. It was first proposed by Wanderman and Piran (2010), who inverted the observed redshift and luminosity distributions of *Swift* long GRBs to obtain a functional form of the rate density.

### 2.2.2.2 Merger GRBs

GRBs produced by the merging of two neutron stars (BNS) or a neutron star and black hole (NS-BH) are also thought to follow the SFR, but with some time delay. BNS and NS-BH mergers can arise from the either evolution of massive stars in a primordial binary (i.e. the system was born as a binary) (Sana et al., 2012) or by dynamical capture in globular clusters (Ye et al., 2019). In primordial systems, the time delay between binary formation and merger is driven by the GW inspiral time, which is strongly dependent on the initial system separation (Sana et al., 2012). Some systems are thus expected to drift away from the star-forming regions in which they formed. They may also incur larger separations when the stars undergo SN
explosion, evolving into compact objects and imparting natal kicks to the system. The stars eventually merge, and may produce a GRB.

Although both BNS and NS-BH systems are predicted to form GRBs, currently only BNS mergers have been associated with GRBs (Abbott et al., 2017a). NS-BH mergers are not as likely to produce GRBs since, in order to release matter into the surrounding environment, the BH must tidally disrupt the NS before merger (Barbieri et al., 2020). The tidal disruption radius is proportional to the mass ratio of the binary, and at large radii, the tidal force of the BH is unlikely to shear the NS, unless the BH mass is small or the NS has high deformability (Barbieri et al., 2020). Therefore, NS-BH mergers are expected to produce a relatively smaller fraction of GRBs than BNS mergers.

The rate density of GRBs with merger origin can be assumed to be proportional to that of BNS mergers. Massive stars produce neutron stars, so BNS mergers are thought to follow the SFR, but with a delay time distribution, $P(t_d)$, to incorporate the period between binary formation and merger:

$$R_{GRB}(z) = \rho_0 \frac{R_M(z)}{R_M(0)}$$

(2.10)

where the rate is normalized to the local GRB rate $\rho_0$ and the BNS merger rate is given by

$$R_M(z) = \int_{t_{\text{min}}}^{t_{\text{max}}} SFR(z_f)P(t_d)dt_d$$

(2.11)
where $z_f$ is the redshift at which the binary is formed. The time delay is calculated as the difference in lookback times between $z_f$ and $z$:

$$t_d = t_{LB}(z) - t_{LB}(z_f) = \frac{1}{H_0} \int_z^{z_f} \frac{dz}{\sqrt{\Omega_m(1+z) + \Omega_\Lambda}}$$

where I have assumed a flat spacetime (Hogg, 1999).

The local rate density to GRBs from BNS mergers, the minimum delay time, and the delay time distribution are all highly uncertain. The local rate density has been probed by a number of GRB studies, yielding values of $\sim 1$ up to a few tens Gpc$^{-3}$ yr$^{-1}$ (Abbott et al., 2017a, 2022; Dietz, 2011; Ghirlanda et al., 2016; Guetta and Piran, 2006; Patricelli et al., 2022; Salafia et al., 2020; Tan et al., 2018; Zhang and Wang, 2018). The GRB rate is naturally affected by the BNS rate. Historically, estimates of the BNS merger rate have come from observations of Galactic BNS systems (Beniamini and Piran, 2016), but increasingly stronger constraints are being made from GW observations with the LVK detectors, with the latest estimate of the BNS is 10-1700 mergers Gpc$^{-3}$ yr$^{-1}$ (Abbott et al., 2021b,d). The delay time distribution incorporates knowledge of the birth properties of compact object binaries and their evolutionary processes. Population synthesis studies of BNS systems tend to find to power law distribution with a slope $t^{-1}$ and minimum delay $> 10$ Myr (Belczynski et al., 2018).
2.2.3 GRB Luminosity Function

The luminosity function of GRBs, \( \Phi(L) \), is traditionally defined as the number of GRBs within the luminosity interval \( dL \). Luminosities are calculated in the standard gamma-ray bandpass of \( 1 - 10^4 \) keV either averaged over the \( T_{90} \) duration or at the peak flux interval of burst emission. Given that most GRBs do not have an opening angle measurement (Racusin et al., 2009), they are also converted to isotropic-equivalent values. The canonical GRB luminosity function is modelled as a broken power law:

\[
\Phi(L) \propto \begin{cases} 
(L/L_b)\alpha_L, & L < L_b \\
(L/L_b)\beta_L, & L > L_b 
\end{cases}
\]  

(2.13)

where \( \alpha_L \) is the low-luminosity slope, \( \beta_L \) is the high-luminosity slope, and \( L_b \) is the break. For long GRBs with peak luminosities greater than \( 10^{50} \) ergs s\(^{-1} \), \( \alpha_L \sim -1 \) and \( \beta_L \sim -2 \) with \( L_b \sim 10^{52} - 10^{53} \) ergs s\(^{-1} \) (Ghirlanda and Salvaterra, 2022; Howell et al., 2014; Lien et al., 2014; Pescalli et al., 2016; Wanderman and Piran, 2010). The luminosity function for short GRBs is less well-constrained, as only a small fraction of short GRBs have measured redshift (Fong et al., 2015). Typical values are \( \alpha_L \sim -1 \) and \( \beta_L \sim -3 \) with \( L_b \sim 10^{52} \) ergs s\(^{-1} \), and are highly dependent on the minimum luminosity assumed (Ghirlanda et al., 2016; Guetta and Piran, 2006; Wanderman and Piran, 2015).

Several authors have suggested that the long GRB luminosity function evolves with the redshift (e.g., (Ghirlanda and Salvaterra, 2022; Pescalli et al., 2016; Petrosian et al., 2015)). Interestingly, most GRBs associated with SNe are found nearby (\( z < 1 \))
and have luminosities lower than the rest of the long GRB population (Cano et al., 2017). This could be due to intrinsic weakness, the fact that larger viewing angles are more available at close distances, or cosmic metallicity evolution.

Another complication for the luminosity function is incorporating angular jet structure (Salafia et al., 2015). When investigating the GRB luminosity function, it is most often modelled for top-hat jets, where the angular distribution of energy across the jet is assumed to be constant. Observations suggest that GRBs instead have some angular structure that could be quasi-universal in nature (Rossi et al., 2002; Zhang and Meszaros, 2002) or arise from from properties of the jet and its interaction with the progenitor ambient medium (Zhang, 2018). Hydrodynamic simulations have also shown that jet structure for long and short GRBs can be strongly dependent on the density of the progenitor star and/or the surrounding environment – in some cases demonstrating that jets can be ”choked,” or unsuccessful in breaking out from the photospheric region or merger ejecta (Granot, 2006; Lazzati and Begelman, 2005; Lazzati et al., 2017). The most notable confirmation of jet structure was the observations of the prompt and afterglow emission from GRB 170817A (Abbott et al., 2017a; Alexander et al., 2017; Mooley et al., 2017). GRB 170817A revealed that GRBs can have luminosities down to $\sim 10^{47}$ ergs s$^{-1}$, which is orders of magnitude lower than any other GRB with known redshift (Abbott et al., 2017a). The low luminosity has been interpreted as being due to off-axis viewing of a structured jet (Mooley et al., 2017, 2018a).

While the GRB luminosity function has also been shown to be consistent with models for structured jets (Pescalli et al., 2015; Salafia et al., 2015), questions remain
about if there is a quasi-universal jet model and how jet structure shapes the intrinsic luminosity function, particularly below $10^{50}$ ergs s$^{-1}$ (Abbott et al., 2022; Banerjee and Guetta, 2022; Beniamini et al., 2018; Salafia et al., 2020; Tan and Yu, 2020).
CHAPTER 3

PAPER IN PROGRESS: CONSTRAINING THE RATE AND LUMINOSITY FUNCTION OF FERMI-GBM GRBS

3.1 Introduction

Gamma-ray bursts (GRBs) are among the most luminous objects in the Universe, formed by the core-collapse of massive stars and the merging of compact binary systems hosting at least one neutron star (Abbott et al., 2017a; Galama et al., 1999). They are also one of the few sources to be observed at high redshifts (Cucchiara et al., 2011; Tanvir et al., 2009). As they are observed independently of their host galaxy luminosities, they are potential probes of early star formation history, where unbiased measurements using standard tracers (e.g., UV light from star-forming galaxies and IR from interstellar dust) are challenging to obtain (Madau and Dickinson, 2014; Wijers et al., 1998; Yüksel et al., 2008). Multi-messenger observations of GRBs and gravitational waves (GWs) also have the capability to help inform compact object evolution by constraining compact binary merger rates and delay time distributions (Abbott et al., 2022; Sarin et al., 2022; Wanderman and Piran, 2015; Zevin et al., 2022).
Rendering GRBs as cosmic probes requires detailed knowledge of their rate densities and luminosity functions, which are still not well understood despite numerous studies (e.g., Abbott et al. 2017a, 2022; Banerjee and Guetta 2022; Ghirlanda and Salvaterra 2022; Ghirlanda et al. 2016; Guetta and Piran 2006; Guetta et al. 2005; Guo et al. 2020; Howell et al. 2014; Lien et al. 2014; Patricelli et al. 2022; Pescalli et al. 2015; Pescalli et al. 2016; Petrosian et al. 2015; Porciani and Madau 2001; Salafia et al. 2020; Tan and Yu 2020; Tsvetkova et al. 2017; Wanderman and Piran 2010, 2015). This is in large part due to the paucity of GRB redshift measurements – only ~6% (~30%) of Fermi (Swift) GRBs have redshifts (Lien et al., 2016; Poolakkil et al., 2021) – and uncertainties surrounding the faint end of the GRB luminosity function. Selection effects and observational biases plague these distributions (Coward et al., 2013), and further complications arise when incorporating the angular distribution of GRB jets (Abbott et al., 2021a; Howell et al., 2019; Salafia et al., 2020). There have been attempts to supplement the observed redshift and luminosity distributions via empirical correlations, such as the lag-luminosity relation (Norris et al., 2000), the $\theta_j - E_{\gamma,iso}$ relation (Frail et al., 2001), the $E_p - L_{\gamma,iso}$ relation (Amati et al., 2002; Yonetoku et al., 2011), the $E_p - E_{\gamma}$ relation (Ghirlanda et al., 2004), and others. However, these correlations are often limited to bright GRBs and do not always extrapolate to the entire population.

Furthermore, less than 1% of all GRBs have a known progenitor, making the distinction between GRBs from collapsars and GRBs from BNS mergers nebulous. GRBs are therefore typically classified by the $T_{90}$ duration, where long ($T_{90} > 2$ s) GRBs are assumed to originate from collapsars and short ($T_{90} < 2$ s) GRBs are as-
sumed to form from BNS mergers. $T_{90}$ is detector-dependent (Jespersen et al., 2020; Qin et al., 2012), and Bromberg et al. (2013) found that up to 35% of short GRBs observed by Swift could actually be GRBs from collapsars. Recently, there have been direct observations to challenge the $T_{90}$ classification: short GRB 200826A ($T_{90} = 1.1$ s) was found in coincidence with optical emission consistent with a SN origin (Ahu-mada et al., 2021) and long GRB 211211A ($T_{90} = 1.1$ s) has been associated with a potential kilonova (Rastinejad et al., 2022), which is a mildly relativistic transient known to be produced from a BNS merger (Barnes and Kasen, 2013; Kulkarni, 2005; Metzger et al., 2010; Tanaka and Hotokezaka, 2013). Notably, GRB 170817A associated to the BNS merger GW170817 also has a $T_{90} = 2.0$ s; though when also considering spectral hardness, GRB 170817A has a $\sim 72\%$ probability of belonging to the short population.

In this work, a $T_{90}$-independent approach is undertaken to constrain the rate densities and luminosity functions of GRBs from collapsars and mergers. Functional forms for the rates and the luminosity functions are assumed and forward-folded through a simulated GBM detection algorithm to fit the Fermi GBM peak flux and luminosity distributions. Of the models tested, the data is best-fit with a GRB population composed of $\sim 55\%$ from collapsars and $\sim 45\%$ from BNS mergers. The collapsar GRBs are best described by a normalized star formation rate with a local event rate of $3.9^{+9.9}_{-3.3}$ Gpc$^{-3}$ yr$^{-1}$ and a broken power law luminosity function with indices $\alpha_L = -1.5^{+1.1}_{-0.2}$ and $\beta_L = -2.0^{+0.5}_{-1.7}$ and a break constrained between $\log_{10}L_c^C = 52.8^{+1.9}_{-3.2}$ ergs s$^{-1}$. The GRBs from BNS mergers are best described by a delayed star formation rate ($P(t_d) \propto t_d^{-1}$) with a local event rate of $3.2^{+27.0}_{-2.4}$ Gpc$^{-3}$ yr$^{-1}$ and
a cut-off power law luminosity function with index $\alpha_L = -0.5^{+0.4}_{-0.5}$ and a break at $\log_{10} L_{c}^{M} = 51.6^{+0.7}_{-0.7}$ ergs s$^{-1}$.

The structure of this paper is as follows. A description of the GBM instrument and the data used is given in Section 3.2. In Section 3.3, the theoretical framework and models for the rate densities and luminosity functions are detailed. The procedure for fitting the data via Bayesian analysis is outlined in Section 3.4. The results from applying the method to GBM data are shown in Section 3.5 and discussed in Section 3.6. Finally, this paper is concluded in Section 4.4 with suggestions on how to extend this work for future analyses.

3.2 Instrument and Data

3.2.1 Fermi GBM

The Fermi GBM is a wide-field ($> 7$ sr) survey instrument with 12 sodium-iodide (NaI) and 2 bismuth germanate (BGO) scintillation detectors that together span an energy range of 8 keV-40 MeV (Meegan et al., 2009). Incident gamma rays interact with the detector crystals to produce lower-energy photons, which are collected by photomultiplier tubes and converted to electronic signals. The NaI detectors have an approximately cosine response with respect to the angle of incidence, and relative rates between the detectors are used to reconstruct localizations to an accuracy of a few degrees (Connaughton et al., 2015; Goldstein et al., 2020). The BGO detectors are only semi-directional but provide spectral sensitivity above $\sim 250$ keV.
The GBM triggers on approximately 240 GRBs per year, making it the most prolific GRB detector currently in operation (von Kienlin et al., 2020). The flight software continually monitors $\sim 30$ trigger algorithms based on energy-timescale combinations to find simultaneous count rate increases above background in at least 2 NaI detectors (Meegan et al., 2009; von Kienlin et al., 2020). The triggering energy ranges are 25-50 keV, 50–300 keV, $> 100$ keV, and $> 300$ keV for the NaI detectors and 2–40 MeV for the BGO detectors (von Kienlin et al., 2020). The triggering timescales range from 16 ms to 8.192 s, increasing by a factors of two. The background rate in each detector is calculated by averaging over a trailing interval (nominally 17 s), where the most recent 4 s is excluded (Meegan et al., 2009).

Due to complexities in modelling the trigger algorithms, studies probing the GRB rate often approximate the GBM triggering criteria by a single peak flux threshold (e.g., Abbott et al. 2017a; Ghirlanda and Salvaterra 2022; Ghirlanda et al. 2016; Howell et al. 2019; Patricelli et al. 2022; Wanderman and Piran 2015). The threshold is typically set so as to include 80% – 95% of the peak flux distribution; however, such a threshold cannot properly account for the GBM sensitivity at low fluxes. In forward-folding analyses, the detector sensitivity determines the relative fraction of detected and undetected GRBs, and a single peak flux threshold, particularly at low fluxes, will overestimate the number of intrinsic GRBs. The detection model thus has important implications for luminosity and redshift distributions in this work. Here, the GBM detection efficiency is estimated through simulations that incorporate the

---

1Although 120 trigger algorithms were enabled in GBM flight software before launch, many were found to be redundant in practice and were disabled in July 2009 (Paciesas et al., 2012; von Kienlin et al., 2020).
distribution of GRB spectra as seen by GBM and the GBM detector response to different source locations and spacecraft orientations. More details can be found in Section 3.3.4.

3.2.2 GBM Peak Flux Distribution

The peak flux of a GRB is the maximum flux over a chosen timescale detected during the burst duration and is a measure of the observed peak brightness of the GRB. Peak flux is typically averaged over 1 second for long GRBs and a few tens of milliseconds for short GRBs, and it is calculated for every GRB detected by GBM. The GBM peak flux distribution, therefore, provides a large data sample to work with, and it also introduces less bias than the observed GBM luminosity and redshift distributions. In this work, it is the primary observable used to constrain the intrinsic luminosity and redshift distributions.

The standard GBM calculation of peak flux in photon space is a by-product of the $T_{90}$ analysis. The observed flux in units of detector counts is deconvolved into photon flux by jointly fitting a Comptonized spectrum to background-subtracted counts in all detectors with good viewing angle relative to the source ($\lesssim 60^\circ$) (Paciesas et al., 2012). The photon spectrum is integrated over an interval longer than the burst duration to obtain a flux lightcurve, and the peak photon flux is then the maximum value within a given time (and energy) range. Standard GBM analysis calculates peak fluxes in the 50-300 keV and 10-1000 keV ranges on the 64 ms, 256 ms, and 1024 ms timescales (von Kienlin et al., 2020).
I extract the peak photon fluxes (10-1000 keV) of all GRBs reported in GBM GRB catalog from July 8, 2008 to June 30, 2022. This yields a sample of 3314 GRBs in total. Note, GRB 200415A is removed from the sample as it has been identified as a magnetar giant flare (Burns et al., 2021; Fermi-LAT Collaboration et al., 2021; Roberts et al., 2021; Svinkin et al., 2021).

3.2.3 GBM Luminosity Distribution

The peak flux distribution is degenerate between the luminosity function and rate density (Guetta et al., 2005; Howell et al., 2014). Simulations demonstrate that fitting luminosity data in addition to peak flux data can result in significantly stronger constraints on the parameter distributions (see Appendix B). Therefore, to help constrain the model parameters, the GBM luminosity distribution is also fit. The observed luminosity distribution is likely incomplete, so to combat bias, more weight is given to the fit over the peak flux distribution than that of the luminosity distribution.

Isotropic-equivalent peak luminosities (1 keV–10 MeV) for GRBs observed by GBM between 2008-2018 are taken from Poolakkil et al. (2021), where the spectral fits were performed over the brightest 1-s (64-ms) time bin for long (short) GRBs. GRBs with redshifts obtained through host galaxy emission spectra or host galaxy association are omitted from this sample, as these are biased towards nearby redshifts (Howell et al., 2014; Wanderman and Piran, 2010). This yields a total of sample of 111 luminosities.

\footnote{https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html}
3.3 Theoretical Framework

To probe the intrinsic luminosity functions and rate densities of GRBs from collapsars and mergers, I implement a forward-folding process to fit GBM data to simulated distributions of peak photon flux and luminosity. The peak flux distribution is built by simulating $10^5$ GRBs with random redshifts and luminosities drawn from assumed forms of the intrinsic rate density and luminosity function. Detection criteria are applied to the peak flux distribution in order to emulate the conditions for GBM triggering. The resulting distribution of “detected” GRBs is compared to GBM data using a Bayesian analysis. The assumed models, the peak flux calculation, and the detection method are described in this section. Throughout, the standard ΛCDM cosmological model is assumed with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$) and space-time is flat (i.e., $\Omega_K = 0$) and $\Omega_M = 0.3$.

3.3.1 GRB Luminosity Functions

Three luminosities functions are explored – a single power law ($\Phi_{\text{SPL}}$), a cut-off power law ($\Phi_{\text{CPL}}$), and a broken power law ($\Phi_{\text{BPL}}$):

$$\Phi_{\text{SPL}}(L) \propto L^{\alpha_L}$$

$$\Phi_{\text{CPL}}(L) \propto L^{\alpha_L} \exp(-L/L_c)$$

$$\Phi_{\text{BPL}}(L) \propto \begin{cases} 
(L/L_*)^{\alpha_L}, & L < L_* \\
(L/L_*)^{\beta_L}, & L > L_* 
\end{cases}$$

(3.1)
where $L$ is assumed to be the isotropic peak luminosity (ergs s$^{-1}$) across the bolometric range of 1 keV-10 MeV and $\alpha_L$, $\beta_L$, $L_c$, and $L_*$ are model parameters. The fitting procedure (described in Section 3.4) requires substantial computation time (i.e., $>3$ weeks using 4 core). Therefore, to reduce computational cost, only $\Phi_{BPL}$ is assumed for GRBs from collapsars. All luminosity functions are tested for GRBs from mergers. Note, the integral of each function is normalized to one and luminosities are drawn from the distribution $\Phi(L)dL$. It is also assumed that all jet structure and viewing angle effects are included within the luminosity function. In other words, the above equations describe apparent luminosity functions of GRBs (Salafia et al., 2015).

### 3.3.2 GRB Rate Densities

For GRBs from collapsars, I assume the cosmic SFR from Madau and Fragos (2017), normalized to the GRB local rate density $\rho_C^0$ [Gpc$^{-3}$ yr$^{-1}$]:

$$\text{SFR}(z) = 0.01 \cdot \frac{(1 + z)^2.6}{1 + \left((1 + z)/2.3\right)^{6.2}}$$  

(3.2)

$$R_{\text{GRB}}^{MF}(z) = \rho_C^0 \frac{\text{SFR}(z)}{\text{SFR}(0)}$$  

(3.3)

For GRBs with a merger origin, the rate density is proportional to that of BNS mergers, which also follows the SFR but with a time delay distribution, $P(t_d)$, to incorporate the period between BNS formation and merger:

$$R_M(z) = \int_{t_{\text{min}}}^{t_{\text{max}}} \text{SFR}(z_f)P(t_d)dt_d$$  

(3.4)
where \( z_f \) is the redshift at which the binary is formed. The SFR from Madau and Fragos (2017) is again assumed and \( P(t_d) \) is taken as a power law of \( t_d^{-1} \) with a minimum time delay, \( t_{min} \), of 20 Myr and a maximum delay, \( t_{max} \), equal to the Hubble time. The time delay is calculated according to (2.12), and the rate density is also normalized to the local merger GRB rate \( \rho_0^M \):

\[
R_{GRB}^{BNS}(z) = \rho_0^M \frac{R_M(z)}{R_M(0)}
\]  

(3.5)

For each rate density, the observed redshift distribution is calculated according to Equations (2.6) and (2.7).

### 3.3.3 GRB Peak Flux

The peak flux, \( P \), of a GRB with isotropic peak luminosity, \( L \), and luminosity distance, \( D_L \), is given by

\[
P = \frac{L}{4\pi D_L^2}.
\]  

(3.6)

For a gamma-ray instrument observing within the bandpass \([e_{min}, e_{max}]\), the detected flux is only a fraction of the total emitted flux, which is accounted for by using a detector correction:

\[
C_{det} = \frac{\int_{e_{min}}^{e_{max}} N(E) \, dE}{\int_{1\,\text{keV}}^{10\,\text{MeV}} N(E) \, dE}
\]  

(3.7)

where the integration limits of 1 keV–10 MeV define the bolometric, co-moving band-pass of the GRB photon spectrum, \( N(E) \). For cosmological sources such as GRBs,
redshifting of the spectrum must also be accounted for via a K-correction (Hogg et al., 2002):

$$K = \frac{\int_{(1+z)e_{\text{min}}}^{(1+z)e_{\text{max}}} N(E) \, dE}{\int_{e_{\text{min}}}^{e_{\text{max}}} N(E) \, dE}$$ (3.8)

The final expression for the observed peak photon flux is then

$$P = \frac{L}{4\pi D_L^2} \int_{10\text{MeV}}^{1\text{keV}} \frac{N(E) \, dE}{EN(E)}$$ (3.9)

where it has been assumed that $L$ is in units of energy per second and $N(E)$ is multiplied by $E$ to obtain photon, rather than energy, flux. For all the simulation GRBs, $N(E)$ is modelled by the Band function (Band et al., 1993). The characteristic spectrum of GRBs from collapsars (mergers) is not known, so a typical spectrum of long (short) GRBs is used: $\alpha = -1 (-0.5)$, $\beta = -2.25 (-2.25)$, and source-frame peak energy $E_p = 511 (800)$ keV (Howell et al., 2014; Wanderman and Piran, 2015).

### 3.3.4 GBM Detection Efficiency

Each gamma-ray instrument has a sensitivity threshold below which it will not trigger, and some fraction of GRBs will go undetected within the instrument field of view (FOV). In order to emulate GBM detection, a detection efficiency curve describing the probability of triggering as a function of peak photon flux is simulated. Curves for the 64-ms and 1.024-s timescales are shown in Figure 3.1.

The detection efficiencies are generated by simulating GRBs at random times and from random locations across the sky. Each GRB is also assigned a random spectrum (either from a Comptonized or Band fit) drawn from the GBM GRB spectral
Figure 3.1: Simulated GBM detection probability as a function of peak photon flux (50-300 keV) for the 1024 ms timescale (purple) and the 64 ms timescale (tan).

catalog (Poolakkil et al., 2021). Given the arrival time, the true background rate in each detector is determined, as well as the position and orientation of Fermi. If GBM was in SAA or the source location was occulted by the Earth, then the GRB is rejected. Otherwise, the spectrum is folded through the GBM instrument responses to determine the observed source counts over a given timescale. The source counts and background rate are combined to ascertain the signal-to-noise ratio (SNR) in each detector. If at least 2 NaI detectors have SNR > 4.5, then the GRB is considered detected. The detection efficiency is then the fraction of detected GRBs over the number of GRBs within the FOV during the instrument livetime.

In this work, the 1.024-s curve is used for fits to the GRB sample, since GBM detects bursts most frequently on the 1.024-s timescale (∼ 17% of the time) and the 2.048-s timescale (∼ 16% of the time) (Figure 3.2). While most short GRBs (∼ 40%) are triggered on the 64-ms timescale, using the 1.024-s detection probability curve may yield a peak flux distribution from mergers that extends to lower fluxes than may be observed of short GRBs in GBM data.
3.4 Bayesian Analysis

To constrain the GRB luminosity and rate distributions, I need to estimate the distribution of model parameters that are consistent with both the GBM data and physical limitations imposed by Nature. One of the most powerful tools for fitting data to underlying models is that of Bayesian inference. Bayesian inference estimates the posterior, \( P \), which is the probability of a set of parameters, \( \Theta \), for a given model, \( M \), and a set of data, \( D \). The posterior is constructed using Bayes’ theorem:

\[
P = \frac{P(D|\Theta, M)P(\Theta|M)}{P(D|M)} = \frac{\mathcal{L}(\Theta)\pi(\Theta)}{\mathcal{Z}(\Theta)} \tag{3.10}
\]

where the likelihood \( \mathcal{L}(\Theta) \) is the probability of the data given a model and its parameters, the prior \( \pi(\Theta) \) is the probability of the model parameters, and evidence \( \mathcal{Z}(\Theta) \) is the probability of the data. The evidence can be written more specifically as the
marginal likelihood:

\[ Z \equiv \int_{\Omega_\Theta} \mathcal{L}(\Theta)\pi(\Theta)d\Theta \quad (3.11) \]

where \( \Omega_\Theta \) is the domain of all possible parameter combinations. Even for a small number of parameters, the posterior distribution can be complex, making evaluation difficult and often analytically intractable. Numerical methods, such as Markov Chain Monte Carlo (MCMC; Hogg and Foreman-Mackey 2018), are often employed to find parameters that maximize the likelihood, but it can be challenging for these methods to efficiently explore the full parameter space, particularly when the posterior is highly multi-modal. Nested sampling (Skilling, 2004, 2006), on the other hand, is a method aimed at estimating the evidence by mapping out the entire prior volume and sampling within contours of increasing likelihood. It essentially performs global estimation of the parameter space, which enables it to identify multiple posterior modes. Furthermore, estimating the evidence allows for direct comparison between two models (e.g., \( M_1 \) and \( M_2 \)) through the Bayes factor (i.e., \( P(D|M_1)/P(D|M_2) \)), which is not possible for methods that only sample the posterior (Speagle, 2020). For more details, see Appendix A.

In this work, I use the nested sampling code DYNESTY (Koposov et al., 2022; Speagle, 2020) implemented within BILBY (Ashton et al., 2019; Romero-Shaw et al., 2020). Each run uses 1000 live points, uniform sampling of the prior, and a stopping criterion of \( \ln \Delta Z < 0.1 \). For demonstrations of the method on simulated data, see Appendix B.
3.4.1 Likelihood

For a binned analysis, the likelihood of observing $N_{\text{obs}}^i$ GRBs in bin $i$ when $N_{\text{exp}}^i$ GRBs are expected is given by the Poisson probability distribution:

$$L(D|\Theta) = P(N_{\text{obs}}|N_{\text{exp}}(\Theta)) = \prod_{i=1}^{C} \frac{(N_{\text{exp}}^i)^{N_{\text{obs}}^i} e^{-N_{\text{exp}}^i}}{N_{\text{obs}}^i!}$$  \hspace{1cm} (3.12)

and the log-likelihood can be written as

$$\ln L = \sum_{i=1}^{C} -N_{\text{exp}}^i + N_{\text{obs}}^i \ln N_{\text{exp}}^i - \ln N_{\text{obs}}^i!$$  \hspace{1cm} (3.13)

where $i$ is the bin number and $C$ is the total number of bins. The expected detection rate, $N_{\text{exp}}^i$, takes into account that an instrument observes only a fraction of the sky at a time, does not always have continuous operations, and is limited by flux sensitivity:

$$N_{\text{exp}}^i = N_{\text{GRB}} \times \text{FOV} \times \tau \times f_{\text{det}}^i \times \frac{N_{\text{det}}^i}{N_{\text{det}}}$$  \hspace{1cm} (3.14)

where $N_{\text{GRB}}$ is the total number of GRBs in the Universe that are beamed towards the Earth per time per steradian and is obtained by integrating Equation (2.6) from $z = 0$ to a maximum redshift $z_{\text{max}} = 10$, at which point contributions from the differential co-moving volume element become increasingly negligible and the GRB rate is close to zero. FOV is the instrument field-of-view, $\tau$ is the instrument livetime, and $f_{\text{det}}^i$ is the fraction of detected over simulated GRBs in the $i$th bin. $N_{\text{det}}^i$ is the number of detected GRBs in the $i$th bin and $N_{\text{det}}$ is the total number of detected
GRBs (i.e., the last term in (3.14) is a normalized distribution of detected GRBs).

When simulating GRBs from collapsars and mergers, Equation (3.14) becomes the sum over each population $j$:

$$N_{\text{exp}}^i = \sum_{j=1}^{2} \left( N_{\text{GRB}}^j \times \frac{N_{\text{det}}^{ij}}{N_{\text{det}}} \right) \times \text{FOV} \times \tau \times f_{\text{det}}^i$$ \hspace{1cm} (3.15)

The probability of obtaining a redshift measurement for a GBM GRB depends on many varied and complex factors. The process here is simplified so that the luminosity data is fit to a model distribution normalized to the total number of observed GBM luminosities. In other words, the expected counts in luminosity bin $k$ are calculated as

$$N_{\text{exp}}^k = 111 \times \sum_{j=1}^{2} \frac{N_{\text{det}}^{kj}}{N_{\text{det}}}$$ \hspace{1cm} (3.16)

where $N_{\text{det}}^{kj}$ is the number of detected GRBs from collapsars or mergers. The luminosity likelihood has the same formulation as (3.13) and is added to it to yield the total likelihood.

For every likelihood evaluation, $10^5$ GRBs are simulated from each source population in order to have enough bursts to reduce statistical fluctuations in the modelling. The GBM FOV is taken as 67% of the sky and, accounting for passage through the SAA, a livetime of 85%. The GBM detection probability curve described in Section 3.3.4 gives $f_{\text{det}}$. 

67
Table 3.1: Prior distributions, descriptions, and symbols for the free parameters of the luminosity and rate density models. The letter $X$ can be replaced by $C$ for collapsars or $M$ for mergers. $L^X_*$ and $\rho^X_0$ have units of ergs s$^{-1}$ and Gpc$^{-3}$ yr$^{-1}$, respectively. Note, there is also a constraint that $\alpha^X_L \geq \beta^X_L$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Prior</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha^X_L$</td>
<td>low-luminosity index</td>
<td>$U(-3, 0)$</td>
</tr>
<tr>
<td>$\beta^X_L$</td>
<td>high-luminosity index</td>
<td>$U(-4, 0)$</td>
</tr>
<tr>
<td>$\log_{10} L^C_{c,*}$</td>
<td>collapsar luminosity cut-off/break</td>
<td>$U(49, 55)$</td>
</tr>
<tr>
<td>$\log_{10} L^M_{c,*}$</td>
<td>merger luminosity cut-off/break</td>
<td>$U(47, 54)$</td>
</tr>
<tr>
<td>$\log_{10} \rho^C_0$</td>
<td>collapsar local rate density</td>
<td>$U(-1, 2)$</td>
</tr>
<tr>
<td>$\log_{10} \rho^M_0$</td>
<td>merger local rate density</td>
<td>$U(-1, 3)$</td>
</tr>
</tbody>
</table>

3.4.2 Priors

For each GRB population, there are 4 possible model parameters: the low-luminosity index $\alpha_L$, the high-luminosity index $\beta_L$, the cutoff or break luminosity $L_{c,*}$, and the local rate density $\rho_0$. Uniform priors are chosen for all model parameters and are shown in Table 3.1. To ensure the joint fit includes sufficient contributions from both collapsar and merger populations, the percentage of detected GRBs from mergers is also constrained to 10% – 50% of the total distribution.

For the luminosity function, the upper and lower indices determine the fraction of bursts produced within a given luminosity interval. A constant rate given by $\alpha_L = 0$ is likely unphysical and it is set as the upper bound. The lower bound of $\alpha_L = -3$ is smaller than reports in literature, for either collapsars or mergers (Howell et al., 2014;
Lien et al., 2014; Wanderman and Piran, 2010, 2015). Indeed, this bound corresponds to a steep drop in rate of $10^3$ per decade in luminosity, which is difficult to explain with current observations. The bounds for $\beta_L$ are similar, though an additional constraint is placed such that $\alpha_L \geq \beta_L$.

The bounds for $L_c$ and $L_*$ are treated the same and set by observations. The highest (lowest) known peak luminosity (1 keV-10 MeV) of a long GRB observed by GBM is $\sim 1.5 \times 10^{54}$ ($\sim 1.3 \times 10^{49}$) ergs s$^{-1}$ (Poolakkil et al., 2021). Therefore, the maximum (minimum) luminosity for collapsar GRBs is set at $1 \times 10^{55}$ ($1 \times 10^{49}$) ergs s$^{-1}$. For short GRBs, the highest known peak luminosity is $< 1 \times 10^{54}$ and the lowest luminosity is $\sim 2 \times 10^{47}$ ergs s$^{-1}$ (Abbott et al., 2017a). The maximum luminosity for GRBs from mergers is set at $1 \times 10^{54}$ ergs s$^{-1}$; however, two different minimum luminosities are tested: $1 \times 10^{49}$ ergs s$^{-1}$ and $1 \times 10^{47}$ ergs s$^{-1}$. The former considers the bulk of the luminosity distribution observed by GBM, while the latter takes into account the observations of GRB 170817A.

The local rate densities are not well constrained, particularly for GRBs with luminosities $< 10^{50}$ ergs s$^{-1}$. For collapsar GRBs, the local rate density has been constrained to be $\lesssim 1000$ Gpc$^{-3}$ yr$^{-1}$ (i.e., $\lesssim 1\%$ of the local core-collapse rate) (Gal-Yam et al., 2006). Furthermore, studies with *Swift* observations typically find $\rho_0 \sim 1$ Gpc$^{-3}$ yr$^{-1}$ (Lien et al., 2014; Wanderman and Piran, 2010). Therefore, an upper bound of $100$ Gpc$^{-3}$ yr$^{-1}$ is chosen. For GRBs from BNS mergers, the upper bound on the local rate density is taken as $1000$ Gpc$^{-3}$ yr$^{-1}$, which encompasses the inferred median for BNS mergers from GW observations (Abbott et al., 2021d).
3.5 Results

The results from fits to the GBM peak flux and peak luminosity distributions are shown in Table 3.2 and Table 3.3. The former is obtained using the minimum luminosity for merger GRBs of $1 \times 10^{47}$ ergs s$^{-1}$, while the latter results are obtained using the minimum luminosity of $1 \times 10^{49}$ ergs s$^{-1}$. Despite the difference in luminosity range, the model results largely agree within the 90% credible regions. Using the evidences to calculate Bayes Factors, the models with the cut-off power law luminosity function, $\Phi_{\text{CPL}}$, are found to be strongly favored with Bayes Factors $\gg 100$. For the collapsar GRB distribution, the models yield a local rate density of $\sim 3.5 - 4.0$ Gpc$^{-3}$ yr$^{-1}$ and a broken power law luminosity function roughly described by $\alpha \sim -1.5$, $\beta \sim -2$, and a break at $\sim 1 \times 10^{52-53}$ ergs s$^{-1}$. For the merger GRB distribution, the local rate density is found to be between $\sim 3 - 4$ Gpc$^{-3}$ yr$^{-1}$ and the luminosity function is described by $\alpha \sim -0.5$ with a cut-off around $4 \times 10^{51}$ ergs s$^{-1}$. The parameter posterior distributions for these models are shown in Figure 3.3 and Figure 3.4. The distributions are remarkably similar and most parameters are relatively well constrained, with the greatest uncertainty arising from the collapsar luminosity break, $L^C_C$.

It is worth mentioning that for the merger GRB population the broken power law luminosity function, $\Phi_{\text{BPL}}^M$, is also preferred over the single power law luminosity function, $\Phi_{\text{SPL}}^M$. For the results in Table 3.2, the Bayes Factor between the two models is $\gg 100$; while for the high luminosity results in Table 3.3, the Bayes Factor is $\sim 10$, indicating only moderately strong preference for $\Phi_{\text{BPL}}^M$. This is likely because it is
Table 3.2: Results from fitting the GBM 1-s peak flux distribution and peak luminosity distribution with the minimum luminosity of $1 \times 10^{47}$ ergs s$^{-1}$. Posterior medians are reported with 90% uncertainties.

<table>
<thead>
<tr>
<th>Model</th>
<th>$\log_{10}\rho_0^M$ (Gpc$^{-3}$ yr$^{-1}$)</th>
<th>$\alpha_L^C$</th>
<th>$\beta_L^C$</th>
<th>$\log_{10}L_C^C$ (ergs s$^{-1}$)</th>
<th>$\alpha_L^M$</th>
<th>$\beta_L^M$</th>
<th>$\log_{10}L_M^M$ (ergs s$^{-1}$)</th>
<th>$\ln Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_{BPL+\Phi^M_{SPL}}$</td>
<td>$0.82_{-0.89}^{+0.93}$</td>
<td>$-1.51_{-0.31}^{+1.15}$</td>
<td>$-2.08_{-1.60}^{+0.60}$</td>
<td>$52.40_{-2.06}^{+2.39}$</td>
<td>$1.15_{-1.90}^{+0.65}$</td>
<td>$-1.39_{-0.40}^{+0.44}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Phi_{BPL+\Phi^M_{CPL}}$</td>
<td>$0.59_{-0.85}^{+0.55}$</td>
<td>$-1.50_{-0.24}^{+1.10}$</td>
<td>$-2.04_{-1.70}^{+0.46}$</td>
<td>$52.79_{-3.22}^{+1.91}$</td>
<td>$0.50_{-0.61}^{+0.98}$</td>
<td>$-0.48_{-0.52}^{+0.44}$</td>
<td>-</td>
<td>51.63_{-0.74}^{+0.73}</td>
</tr>
<tr>
<td>$\Phi_{CPL+\Phi^M_{BPL}}$</td>
<td>$0.60_{-0.88}^{+0.85}$</td>
<td>$-1.42_{-0.39}^{+1.01}$</td>
<td>$-2.04_{-1.50}^{+0.42}$</td>
<td>$52.81_{-3.18}^{+1.97}$</td>
<td>$0.35_{-0.73}^{+1.28}$</td>
<td>$-0.56_{-0.52}^{+0.52}$</td>
<td>$-3.06_{-0.68}^{+1.28}$</td>
<td>51.69_{-1.39}^{+0.77}</td>
</tr>
</tbody>
</table>

Table 3.3: Same as Table 3.2 but using the minimum luminosity of $1 \times 10^{49}$ ergs s$^{-1}$.

<table>
<thead>
<tr>
<th>Model</th>
<th>$\log_{10}\rho_0^M$ (Gpc$^{-3}$ yr$^{-1}$)</th>
<th>$\alpha_L^C$</th>
<th>$\beta_L^C$</th>
<th>$\log_{10}L_C^C$ (ergs s$^{-1}$)</th>
<th>$\alpha_L^M$</th>
<th>$\beta_L^M$</th>
<th>$\log_{10}L_M^M$ (ergs s$^{-1}$)</th>
<th>$\ln Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_{BPL+\Phi^M_{SPL}}$</td>
<td>$0.14_{-0.64}^{+0.84}$</td>
<td>$-1.04_{-0.63}^{+0.90}$</td>
<td>$-1.93_{-1.47}^{+0.35}$</td>
<td>$51.93_{-1.71}^{+2.23}$</td>
<td>$2.12_{-1.08}^{+1.17}$</td>
<td>$-2.09_{-0.49}^{+0.46}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Phi_{BPL+\Phi^M_{CPL}}$</td>
<td>$0.55_{-0.80}^{+0.54}$</td>
<td>$-1.47_{-0.25}^{+1.09}$</td>
<td>$-1.94_{-1.66}^{+0.35}$</td>
<td>$52.51_{-3.04}^{+2.12}$</td>
<td>$0.60_{-0.90}^{+1.16}$</td>
<td>$-0.55_{-0.91}^{+0.51}$</td>
<td>-</td>
<td>51.64_{-0.83}^{+0.64}</td>
</tr>
<tr>
<td>$\Phi_{BPL+\Phi^M_{BPL}}$</td>
<td>$0.58_{-0.77}^{+0.67}$</td>
<td>$-1.41_{-0.33}^{+1.14}$</td>
<td>$-1.97_{-1.77}^{+0.38}$</td>
<td>$52.51_{-3.07}^{+2.12}$</td>
<td>$0.56_{-0.73}^{+1.65}$</td>
<td>$-0.61_{-1.26}^{+0.54}$</td>
<td>$-3.07_{-0.82}^{+1.13}$</td>
<td>51.59_{-1.30}^{+0.95}</td>
</tr>
</tbody>
</table>
Figure 3.3: Posterior probability distributions from using $R^M_{GRB}$ and $\Phi^C_{BPL}$ for collapsar GRBs and $R^B_{GRB}$ and $\Phi^M_{CPL}$ for merger GRBs. A minimum luminosity of $1 \times 10^{47}$ ergs s$^{-1}$ is assumed. Medians (solid red lines) and 90% credible intervals (blue dashed lines) are printed above the 1D histograms. Contours indicate the 0.5-, 1-, 1.5, and 2-sigma confidence intervals.

more difficult to fit the data with a single power law over the larger luminosity range.

For the remainder of this work, the model of $\Phi^C_{BPL} + \Phi^M_{CPL}$ with the minimum luminosity of $1 \times 10^{47}$ ergs s$^{-1}$ is selected for further analysis. The best-fit parameters of this model are $\rho^C_0 = 3.9^{+9.9}_{-3.3}$ Gpc$^{-3}$ yr$^{-1}$, $\alpha_L = -1.5^{+1.1}_{-0.2}$, $\beta_L = -2.0^{+0.5}_{-1.7}$, $\log_{10} L^C_c =$
52.8_{-3.2}^{+1.9} \ ergs \ s^{-1}, \ \rho_0^M = 3.2_{-2.4}^{+2.7} \ Gpc^{-3} \ yr^{-1}, \ \alpha_L = -0.5_{-0.5}^{+0.4}, \ and \ log_{10}L^* = 51.6_{-0.7}^{+0.7} \ ergs \ s^{-1}. \ The \ posterior \ predictive \ distributions \ of \ peak \ flux \ and \ isotropic \ luminosity \ for \ this \ model \ are \ shown \ in \ Figure \ 3.5. \ The \ model \ fit \ to \ the \ GBM \ peak \ flux \ distribution \ is \ largely \ consistent \ with \ the \ data, \ with \ the \ greatest \ deviation \ arising \ at \ low \ peak \ fluxes. \ This \ is \ a \ result \ of \ the \ single \ timescale \ detection \ algorithm \ and \ is \ discussed \ in \ Figure \ 3.4: \ Same \ as \ Figure \ 3.3 \ but \ for \ using \ the \ minimum \ luminosity \ of \ 1 \times 10^{49} \ ergs \ s^{-1}.\]
Figure 3.5: Predictive posterior distributions for the 1-s peak flux (left) and isotropic peak luminosity (right) distributions of GBM GRBs. Model distributions resulting from random draws from the posterior are depicted in blue, while that from the posterior median is shown in red. The GBM data is presented in black.

Section 3.6.3. The fit to the GBM luminosity distribution is also consistent with the data.

3.6 Discussion

3.6.1 Astrophysical Implications

The all-sky rate of GRBs that are beamed towards Earth per year is found to be $2.03^{+7.96}_{-1.69} \times 10^4$, of which $4.51^{+39.0}_{-3.39} \times 10^3$ result from BNS mergers, where the reported uncertainties are the 90% credible regions. There are $1.15^{+4.51}_{-0.96} \times 10^4$ GRBs within the GBM FOV per year and, given the mock trigger algorithm, a GBM detection rate of $257^{+1224}_{-227}$ GRBs per year with $116^{+1215}_{-108}$ from BNS mergers\(^3\). This is illustrated in Figure 3.6, where it can be seen that only the bright tails of the intrinsic peak flux

\(^3\)Although the detection fraction of GRBs from BNS mergers was constrained between 10%-50%, due to the large uncertainties and skewness of the posterior, random samples from the marginalized parameter distributions can yield higher percentages.
Figure 3.6: The intrinsic and observed peak flux and luminosity distributions obtained using the parameter posterior medians of the $\Phi_{C}^{BPL}+\Phi_{M}^{CPL}$ ($\log_{10} L_{\text{min}} = 47$) model. All GRBs arising from collapsars are indicated in green, and those from BNS mergers are in indigo. The detected GRB distribution is shown in red.

...distributions are observed. Likewise, the observed luminosity distribution is only a small fraction of the intrinsic distribution. GBM detects $\sim 240$ GRBs per year of which approximately 40 are short GRBs (von Kienlin et al., 2020). The total model detection rate roughly agrees with the GBM rate; however the median number of detections from BNS mergers suggests that a larger fraction of the long GRB population could actually arise from BNS mergers, as hinted at by the broadband observations of GRB 211211A and its kilonova (Rastinejad et al., 2022; Troja et al., 2022). Interestingly, an instrument approximately an order of magnitude more sensitive than GBM could recover the peak of the intrinsic peak flux distribution from BNS mergers, which could likely set much tighter constraints.

Wanderman and Piran (2015) quantify the contamination of the GRB distribution from non-collapsars (i.e., mergers) with those from collapsars. They find that 20%–40% of Swift short GRBs follow the SFR, rather than following a delayed rate...
density as is expected for GRBs from BNS mergers, and suggest that this is a population of collapsar GRBs masquerading as merger GRBs. This is in good agreement with conclusions from Bromberg et al. (2013), who analyze the $T_{90}$ distribution observed by different gamma-ray instruments and contend that 40% of Swift (and 15%–20% of Fermi) short GRBs actually originate from collapsars. Burns et al. (2016), however, utilize ground-based analysis of short GRBs and estimate a lower contamination rate of only $\sim 10\%$ for Swift. Without temporal information, the long/short contamination rate from this study cannot be precisely determined. However, given that the best-fit model predicts that 45% (28%–89%; 90% credible interval) of GBM GRBs are of BNS merger origin, these findings likely imply a smaller contamination rate of the short GRB population by collapsars and a higher contamination rate of the long GRB distribution by non-collapsars.

The GRB rate from collapsars can also be compared to the core-collapse supernova rate. As inferred from above, the model all-sky rate of GRBs from collapsars is $1.58^{+4.06}_{-1.35} \times 10^4$ per year that are beamed towards the Earth. Assuming a median opening angle of $5.4^\circ$ (Racusin et al., 2009), the model predicts $\sim 3.56^{+9.15}_{-3.05} \times 10^6$ GRBs from collapsars across the universe per year. The total core-collapse supernovae (CCSNe) rate can be estimated by multiplying the SFR from Madau and Fragos (2017) by the efficiency to forming CCSNe. Assuming an efficiency of $0.0068 \, M_{\odot}^{-1}$ for a Salpeter initial mass function (Madau and Dickinson, 2014), the total core-collapse supernova rate in the universe is found to be $\sim 2.25 \times 10^8$ per year. About $\sim 25\%$ of all core-collapse supernovae are Type Ibc (Li et al. 2011) and only $\sim 1\%$ of all Type Ibc supernovae are related to GRBs (Gal-Yam et al., 2006), yielding approximately
**Figure 3.7:** The rate density for GRBs from collapsars using the 90% parameter posterior credible intervals (green). The beaming-corrected rate assuming $\theta_j = 5.4^\circ$ is shown in blue. This is compared to the rate of Type Ibc SNe (solid red line) from Madau and Dickinson (2014) and the predicted rate of GRBs assuming 1% of Type Ibc SNe produce GRBs (dashed red line).

$5.6 \times 10^5$ GRBs from Type Ibc SNe every year. This implies that (1) the true all-sky rate is closer to the lower end of the 90% credible region, (2) the median GRB opening angle is $\gtrsim 10^\circ$, or (3) a larger fraction of Type Ibc SNe produce GRBs. Although jet opening angle measurements are difficult and rare, observations currently constrain most $\theta_j < 10^\circ$ for long GRBs (Goldstein et al., 2016b; Racusin et al., 2009); therefore, (2) may not be likely. The SN/GRB ratio is also currently under study (e.g., Ho et al. (2022)). Future studies can help determine whether (1) or (3) is a more likely scenario. The rates from the posterior results are compared to those expected from Type Ibc in Figure 3.7.

Similarly, the GRB rate from BNS mergers can be examined. Assuming the BNS rate density with a power law time delay distribution with index -1 and a minimum delay of 20 Myr, the local rate of GRBs from BNS mergers is found to be
Figure 3.8: The rate density for GRBs from BNS mergers using the 90% parameter posterior credible intervals (purple). The beaming-corrected rate assuming $\theta_j = 10^\circ$ is shown in light blue. This is compared to the BNS rate estimated from GW observations (dashed red lines).

$3.2_{-2.4}^{+27.0}$ Gpc$^{-3}$ yr$^{-1}$ that are beamed towards the Earth. Although the jet opening angle distribution for short GRBs is highly unconstrained, a median opening angle of $10^\circ$ is assumed (Fong et al., 2015). This implies between $\sim 50 - 1770$ GRBs are produced by BNS mergers in the local universe. Recent GW observations have constrained the local rate to BNS mergers to between $17 - 1700$ Gpc$^{-3}$ yr$^{-1}$ (Abbott et al., 2021d). Future upgrades to the GW detectors will allow for deeper observations and tighter constraints on the BNS/GRB ratio beyond the local universe (Abbott et al., 2020b). More measurements of jet opening angles from GRBs produced by BNS mergers will also help refine the beaming-corrected GRB rate.

3.6.2 Comparison With Previous Works

No previous studies have fit the GBM peak flux distribution with both long and short GRBs, so direct comparisons must be made with caution. This is particularly
true for the merger GRB results since, due to the simplified GBM detection curve, a 1-s, rather than the 64-ms, luminosity function is assumed. That said, it is instructive to compare the results from this combined fit to that obtained by separate fits to GRB data.

Wanderman and Piran (2010) perform a study of Swift long GRBs by inverting the observed redshift and luminosity distributions and using a Monte Carlo maximum likelihood technique to find the intrinsic distributions. They only consider GRBs with a redshift obtained from afterglow observations. To estimate the probability of detection and the probability of obtaining a redshift measurement, they also adopt empirical functions based on peak flux. They obtain a broken power law for the rate density with $\rho_0^C \sim 1.3 \text{ Gpc}^{-3} \text{ yr}^{-1}$. They also find a broken power law luminosity function with $\alpha_L^C \sim -1.2$, $\beta_L^C \sim -2.4$, and a break at $L^* \sim 10^{52.5} \text{ ergs s}^{-1}$ for $L \geq 1 \times 10^{50} \text{ ergs s}^{-1}$. These values are consistent with the best-fit parameters of the collapsar GRB distribution found in this study.

Lien et al. (2014) take a forward-folding approach to constrain the GRB redshift and luminosity distributions of long GRBs. In particular, they perform detailed simulations of the Swift-BAT trigger algorithms to obtain the BAT detection probability to long GRBs. They assume the functional form of the GRB rate found by Wanderman and Piran (2010) and a broken power law for the luminosity function. Each GRB is simulated with a Band spectrum but given spectral indices randomly drawn from Sakamoto et al. (2009). Different $E_p$ distributions are also tested. To estimate temporal features, each mock GRB is assigned a random rest-frame lightcurve from a template bank of BAT GRB pulse shapes. The BAT peak flux, redshift, lumi-
nosity, and $E_p$ distributions are fit using an MCMC sampling method. They obtain model parameters: $\rho_0^C \sim 0.42 \text{ Gpc}^{-3} \text{ yr}^{-1}$, $\alpha_L^C \sim -0.65$, $\beta_L^C \sim -3.0$, and $L_{c,*} \sim 10^{52}$ ergs s$^{-1}$. While these values are somewhat different that those in (Wanderman and Piran, 2010), they are largely consistent given the different methods and assumptions. Again, the best-fit parameters of the collapsar GRBs largely agree with Lien et al. (2014). With the smaller local rate, they do however find an all-sky rate of long GRBs to be $\sim 4600 \text{ Gpc}^{-3} \text{ yr}^{-1}$, which yields a closer rate to the CCNSe under the same assumptions detailed above.

Wanderman and Piran (2015) take a similar approach to their earlier study to constrain the peak flux, rate, and luminosity distributions of short GRBs. The 64-ms peak fluxes of short GRBs are taken from BATSE and Fermi, with thresholds of 1.5 ph cm$^{-2}$ s$^{-1}$ and 2.37 ph cm$^{-2}$ s$^{-1}$, respectively. Redshifts are obtained from Swift, and due to small sample size, all redshifts are used, regardless of type. A broken power law luminosity function is assumed, and two different SFRs are tested with two different delay distributions: (1) a power-law with the slope as a free parameter and a minimum delay of 20 Myr and (2) a log-normal given as a function of $t_d$ and with varying width. Wanderman and Piran (2015) find $\rho_0^M \sim 4.1 \text{ Gpc}^{-3} \text{ yr}^{-1}$, $\alpha_L^M \sim -1.95$, $\beta_L^M \sim -3.0$, and $L_{m,*} = 10^{52.5}$ ergs s$^{-1}$ for $L > 5 \times 10^{49}$ ergs s$^{-1}$. The best-fit parameters of the collapsar GRBs agree within uncertainties.

3.6.3 Method Limitations

There are a few limitations to the method used here. The results greatly depend on the GBM detection algorithm. The fraction of detected bursts affects
the all-sky rate and the local rate. The detection efficiency curves described in Section 3.3.4 only apply to the 1-s and 64-ms GBM triggering timescales. However, multiple timescales are employed by the GBM flight software, and as seen in Figure 3.5, the simulated peak flux distribution obtained with only the 1024 ms timescale cannot entirely replicate the observed distribution, particularly at low fluxes. As can be deduced from Figure 3.1, longer triggering timescales generally allow greater sensitivity to lower fluxes. By incorporating longer flux timescales into the detection algorithm, it may be possible to better reproduce the GBM peak flux distribution. Additionally, lightcurves are not generated for the simulated GRBs. With a lightcurve, the peak flux can be measured on multiple timescales, which would allow for comparison with multiple detection probability curves and/or different data distributions based on flux timescale. To give a temporal scale to the lightcurves, an intrinsic duration distribution for each GRB population could be assumed (although they are highly uncertain; see Zhang (2019)) This, in turn, could allow fits to the GBM $T_{90}$ and fluence distributions, which may be more sensitive to a bi-modal population of GRBs.

Another simplification made here is assuming a single spectrum for collapsar GRBs and another for merger GRBs. The assumed spectra greatly influence the observed peak flux. In fact, Lien et al. (2014) showed that the local rate density to long GRBs depends on the assumed $E_p$ distribution, increasing the rate by up to a factor of 4 from the best-fit value. Therefore a distribution of spectra would likely yield results more representative of the entire GRB population. Many previous works have used the correlations between luminosity and $E_p$ (Amati et al., 2002; Yonetoku et al., 2011) to yield an $E_p$ distribution, one could also directly draw from the GBM
spectral catalog (Poolakkil et al., 2021). Even by this method, it is implied that the spectra for long GRBs represents those from collapsars, and likewise for short/merger GRBs. Until more GRBs are associated with their progenitor, particularly GRBs from mergers, this may be the most fitting assumption.

There are also a variety of avenues to explore with respect to the functional forms of the intrinsic rate densities and the luminosity functions. The commonly-used broken power law rate density from Wanderman and Piran (2010) could be tested and compared to the normalized SFR rate. More parameters in the BNS merger rate could also be allowed to vary (i.e., the index of the time delay distribution and the minimum time delay). Although it is common to assume the parameter values used in this study (e.g., Howell et al. 2019; Wanderman and Piran 2015), Zevin et al. (2022) use the sample of short GRB host galaxies studied in Fong et al. (2022) and Nugent et al. (2022) to place constraints on the BNS formation rate. They find a steep time delay index of $\sim$-1.8 and a large minimum time delay of $\sim$ 170 Myr. Therefore, exploring different BNS rates could lead to different intrinsic GRB distributions. One could also add another contribution of GRBs from NSBH systems. No GRB has yet been associated with a NSBH, but through simulations NSBH systems have been shown to be viable progenitors of some GRBs (Paschalidis et al., 2015; Ruiz et al., 2018; Siegel and Metzger, 2017). The inclusion of NSBHs may yield constraints on the debated intermediate GRB population (Horvath, 2002). Magnetar giant flares have recently been identified as making up $\sim$ 2% of all short GRB detections (Burns et al., 2021); however, the likely MGF candidate in GBM data, GRB 200415A, was removed
in this study. Finally, one could investigate luminosity and/or redshift evolution of the assumed distributions.

3.7 Conclusion

We have built a set of models emulating the Fermi GBM peak flux and luminosity distributions for long and short GRBs. Using a large set of simulated GRBs, we fit the GBM data using assumed models for the intrinsic rate distributions and luminosity functions of GRBs from collapsars and BNS mergers. The data is best fit with GRB population composed of \( \sim 45\% \) originating from BNS mergers. These GRBs are best described by a delayed star formation rate \( (P(t_d) \propto t_d^{-1}) \) with a local event rate of \( 3.2^{+27.0}_{-2.4} \) Gpc\(^{-3}\) yr\(^{-1}\) and a cut-off power law luminosity function with index \( \alpha_L = -0.5^{+0.4}_{-0.5} \) and a break at \( \log_{10} L^M \approx 51.6^{+0.7}_{-0.7} \) ergs s\(^{-1}\). The collapsar GRBs are best described by a normalized star formation rate with a local event rate of \( 3.9^{+9.9}_{-3.3} \) Gpc\(^{-3}\) yr\(^{-1}\), and a broken power law luminosity function with indices \( \alpha_L = -1.5^{+1.1}_{-0.2} \) and \( \beta_L = -2.0^{+0.5}_{-1.7} \) and a break constrained between \( \log_{10} L^C = 52.8^{+1.9}_{-3.2} \) ergs s\(^{-1}\). The best-fit sample suggests that GBM should detect \( \sim 257 \) GRBs per year, which is largely consistent with the true GBM detection rate of \( \sim 240 \) bursts per year (von Kienlin et al., 2020). It also predicts a higher rate of BNS detections than expected (i.e., \( \sim 45\% \)). This is because GBM triggers on \( \sim 40 \) short GRBs per year (von Kienlin et al., 2020), and under the assumption that all long GRBs are produced by collapsars and all short GRBs are formed by BNS mergers, one would expect a lower BNS detection rate of \( \sim 17\% \). Thus, these findings challenge the standard collapsar-long/merger-short assumption.
While the method developed here can be improved, this study shows how much can be learned from the amount of data currently available and highlights the need for (1) more redshift detections and (2) more associations of GRB with their progenitors. Future multi-messenger observations of GWs and GRBs in the next GW observing run (i.e., O4; Abbott et al. (2020b)) will be vital to reducing the uncertainties found here. Also, as shown in Figure 3.6, the observed peak flux distribution is only a small percentage of the true intrinsic distribution. Therefore, it is important to improve detector sensitivities to low fluxes in order to obtain better constraints on the source distributions. Moreover, subthreshold searches, such as those developed for Fermi (Blackburn et al., 2015; Goldstein et al., 2019) and Swift (DeLaunay and Tohuvavohu, 2021), will be also key in this endeavor.
CHAPTER 4

PAPER: A JOINT Fermi-GBM AND LIGO/Virgo ANALYSIS OF COMPACT BINARY MERGERS FROM THE FIRST AND SECOND GRAVITATIONAL-WAVE OBSERVING RUNS

4.1 Introduction

Simultaneous observations of the same source in gravitational waves (GWs) and gamma-rays probe some of the most cataclysmic events in the Universe and create rich opportunities to study fundamental physics, cosmology, and high energy astrophysics. This was demonstrated by the joint observations (Abbott et al., 2017a) of the binary neutron star (BNS) coalescence GW170817 (Abbott et al., 2017c, 2019b) and the short gamma-ray burst GRB 170817A (Goldstein et al., 2017; Savchenko et al., 2017). These observations led to constraints on the speed of gravity (Abbott et al., 2017a), an independent measure of the Hubble constant (Abbott et al., 2017; Abbott et al., 2021a; Hotokezaka et al., 2019), evidence for heavy element production via r-process nucleosynthesis in a kilonova (e.g., Chornock et al. 2017; Cowperthwaite et al. 2017; Kasen et al. 2017; Tanvir et al. 2017; Watson et al. 2019), and more. Motivated by the wealth of science gained from multi-messenger observations such as these, we seek to increase the number of joint GW/gamma-ray detections by per-
forming coordinated analysis of candidates from Advanced LIGO (Aasi et al., 2015), Advanced Virgo (Acernese et al., 2014), and the Fermi Gamma-ray Burst Monitor (GBM; Meegan et al. 2009).

The first LIGO/Virgo science observing run (O1) ran from September 2015 to January 2016, during which GBM performed online analyses of GW candidates from compact binary coalescence (CBC) searches. For GBM offline analysis (Burns et al., 2019), trigger selection was conservative, treating all CBC candidates with a false alarm rate (FAR) of less than $10^{-5}$ Hz (about 1/day) as equally plausible for follow-up. The CBC candidates were used to search for coincidences with GBM-triggered GRBs and subthreshold short GRBs from the offline Untargeted Search (Briggs et al., in prep.). CBC event times were also used to seed more sensitive follow-up with the Targeted Search (Blackburn et al., 2015) of GBM data. No unambiguous coincidences were found between the GBM and LIGO/Virgo candidates. The most significant event found in the GBM follow-up search was associated with the first observed binary black hole (BBH) coalescence, GW150914 (Abbott et al., 2016b). However the GBM candidate, GW150914-GBM, could not be unambiguously claimed as an electromagnetic counterpart due to its extremely weak signal and poor localization (Connaughton et al., 2016, 2018; Greiner et al., 2016).

For the second observing run (O2), running from November 2016 to August 2017, the GBM Targeted Search was improved (Goldstein et al., 2016a) and run autonomously, in low latency, again following up CBC triggers with FAR $< 10^{-5}$ Hz. The most interesting multimessenger event from O2 was the association between GW170817 and GRB 170817A. The Targeted Search proved redundant in this case, as
the GRB produced a trigger onboard Fermi.\footnote{https://gcn.gsfc.nasa.gov/other/524666471.fermi} However, had the source been $\sim 10$ Mpc farther from Earth, it would not have triggered the detectors onboard GBM and would have only been detectable with subthreshold searches (Abbott et al., 2017a; Goldstein et al., 2017), while still being well within the LIGO/Virgo detection horizon (Abbott et al., 2017c).

In this work, we perform an offline follow-up of all CBC triggers published in the first LIGO/Virgo gravitational-wave transient catalog (GWTC-1; Abbott et al. 2019a). Our search methods are akin to LIGO/Virgo searches for GWs coincident with GRBs (Abbott et al., 2019a, 2017b). In addition to seeking coincidences to individual GW events, we search on a statistical basis, looking for any cumulative effects that subthreshold gamma-ray counterparts might have on the resulting follow-up distribution. We improve upon the GBM analysis of O1 triggers in Burns et al. (2019), in that the joint association calculation no longer treats all CBC candidates equally. Instead, the analysis accounts for the astrophysical nature of the CBC candidates as well as their potential visibility with respect to GBM. This is done by incorporating the probability that each CBC candidate originated from an astrophysical rather than terrestrial source and also considering the fraction of LIGO/Virgo localization probability that was observable to GBM at GW trigger time. Finally, we augment GBM follow-up of GW events by also reporting results from a new search method (Stachie et al., 2020) that seeks gamma-rays coincident with LIGO single-interferometer triggers.
This paper is organized as follows. In Section 4.2, we describe the sample of gravitational-wave candidates and the GBM searches used to follow-up this sample. Section 4.3 summarizes the results of these searches, including the search for coincidences with single-interferometer triggers, and discusses the probability of association between the GW and gamma-ray candidate events. In Section 4.4, we conclude and discuss future prospects for GBM follow-up of GWs.

4.2 Method

4.2.1 Gravitational-wave Trigger Selection

The Advanced LIGO (Aasi et al., 2015) and Virgo (Acernese et al., 2014) observatories are kilometer-scale Michelson laser interferometers designed to detect GWs. Multiple search pipelines are used to detect CBC events in strain data, with each pipeline making different assumptions about the signals and the detector noise and using different technical solutions to maximize detection efficiency. We focus on events generated by two pipelines: PyCBC (Usman et al., 2016) and GstLAL (Messick et al., 2017). Both rely on accurate physical models of the gravitational waveform radiated by a CBC event and use the models to perform matched filtering on strain data. The process of matched filtering produces a signal-to-noise ratio (S/N) over a large number of templates covering the CBC parameter space. The extent of the parameter space chosen for O2 and the method used to construct the template bank are described for PyCBC and GstLAL in Dal Canton and Harry (2017) and Mukherjee et al. (2021), respectively. Once the S/N has been calculated over all templates, S/N-
peaks above a certain threshold are recorded as single-detector CBC triggers. Non-Gaussian and non-stationary detector noise frequently produces non-astrophysical triggers with large S/N, hence the pipelines employ a variety of techniques to veto or down-rank such triggers. The surviving triggers are used in a coincidence analysis, and each pair of triggers occurring within the maximum GW travel time between detectors produces a coincident trigger. The coincident trigger is assigned a ranking statistic that takes into account (i) S/N in the GW detectors, (ii) signal-based vetoes indicating the compatibility of the waveform with a CBC signal, and (iii) the probability of the observed combination of S/N, time delay, and phase difference at the different detectors to be produced by an astrophysical signal (e.g. Nitz et al. 2017). The final step is mapping the coincident rank to a statistical significance, which in the case of CBC pipelines is reported via two different quantities: the FAR of the search at the time of the trigger and the probability that the trigger has an astrophysical origin ($p_{\text{astro}}$; Kapadia et al. 2020). $p_{\text{astro}}$ is estimated using our current understanding of the population of real signals weighed against the distribution of background (false signals) due to GW detector noise fluctuations.

We perform GBM follow-up of all 25 CBC triggers reported in the LIGO/Virgo catalog GWTC-1 (Abbott et al., 2019a). This catalog utilized state-of-the-art configurations of PyCBC and GstLAL, as well as the best data-quality selection of the LIGO and Virgo strain data available, for a full reanalysis of O1 and O2. Listed in Table 4.1, the catalog triggers were required to pass an initial threshold of FAR $\lesssim 3.86 \times 10^{-7}$ Hz (about 1/30 days) in at least one pipeline. Triggers passing this FAR threshold and additionally having $p_{\text{astro}}$ greater than 50% are denoted with “GW” in the event
name. In the follow-up analyses, the GBM searches are guided by the CBC trigger times. To assess GBM coverage of the LIGO/Virgo triggers, the public HEALPix (Górski et al., 2005) sky localization maps accompanying GWTC-1 are taken for the high $p_{\text{astro}}$ detections (LIGO Scientific & Virgo Collaboration, 2019). We generate \texttt{Bayestar} skymaps (Singer and Price, 2016) for all remaining triggers which had corresponding GBM data. \texttt{Bayestar} skymaps rely on the mass and spin parameters reported by the searches and do not marginalize over them, as is done instead for high $p_{\text{astro}}$ detections via full parameter estimation (Abbott et al., 2016a; Veitch et al., 2015). Nevertheless, they allow approximations of GBM observing coverages at much lower computational costs. Finally, for each CBC trigger, the maximum $p_{\text{astro}}$ is used between the \texttt{GstLAL} and \texttt{PyCBC} pipelines (Abbott et al., 2019a, Table IV).

4.2.2 \textit{Fermi}-GBM Searches

GBM is a survey instrument aboard the \textit{Fermi} Gamma-ray Space Telescope and is comprised of 14 scintillation detectors that span an energy range of 8 keV to 40 MeV (Meegan et al., 2009). Twelve of the detectors are made of thallium-doped sodium iodide (NaI) crystals and are oriented in such a manner as to cover the entire sky un-occulted by the Earth ($\sim$70%). The two other detectors are bismuth germanate (BGO) crystals positioned on opposite sides of the spacecraft. Triggering algorithms running on the satellite search data on multiple timescales and energy ranges for coherent, statistically-significant (usually $4\sigma$) excesses in at least 2 NaI detectors (Bhat et al. 2016; von Kienlin et al. 2020). Localization is performed by combining the detector responses with a set of three template photon spectra repre-
Table 4.1: Gravitational-wave triggers from Abbott et al. (2019a). The $p_{\text{astro}}$ values shown here are the maximum values reported between the GstLAL and PyCBC pipelines. The percentage of the LIGO/Virgo localization probability that was visible to GBM at trigger time is also given. Triggers with unspecified coverage are due to GBM passage through the South Atlantic Anomaly when all detectors are turned off.

<table>
<thead>
<tr>
<th>LIGO/Virgo</th>
<th>UTC Date</th>
<th>UTC Time</th>
<th>$p_{\text{astro}}$</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW150914</td>
<td>2015-09-14</td>
<td>09:50:45.4</td>
<td>1</td>
<td>66.7%</td>
</tr>
<tr>
<td>151008</td>
<td>2015-10-08</td>
<td>14:09:17.5</td>
<td>0.27</td>
<td>100%</td>
</tr>
<tr>
<td>151012.2</td>
<td>2015-10-12</td>
<td>06:30:45.2</td>
<td>0.023</td>
<td>58.4%</td>
</tr>
<tr>
<td>GW151012</td>
<td>2015-10-12</td>
<td>09:54:43.4</td>
<td>1</td>
<td>66.1%</td>
</tr>
<tr>
<td>151116</td>
<td>2015-11-16</td>
<td>22:41:48.7</td>
<td>$\ll 0.5$</td>
<td>72.6%</td>
</tr>
<tr>
<td>GW151226</td>
<td>2015-12-26</td>
<td>03:38:53.6</td>
<td>1</td>
<td>78.8%</td>
</tr>
<tr>
<td>161202</td>
<td>2016-12-02</td>
<td>03:53:44.9</td>
<td>0.034</td>
<td>-</td>
</tr>
<tr>
<td>161217</td>
<td>2016-12-17</td>
<td>07:16:24.4</td>
<td>0.018</td>
<td>-</td>
</tr>
<tr>
<td>GW170104</td>
<td>2017-01-04</td>
<td>10:11:58.6</td>
<td>1</td>
<td>90.3%</td>
</tr>
<tr>
<td>170208</td>
<td>2017-02-08</td>
<td>10:39:25.8</td>
<td>0.02</td>
<td>97.8%</td>
</tr>
<tr>
<td>170219</td>
<td>2017-02-19</td>
<td>14:04:09.0</td>
<td>0.02</td>
<td>5.1%</td>
</tr>
<tr>
<td>170405</td>
<td>2017-04-05</td>
<td>11:04:52.7</td>
<td>0.004</td>
<td>-</td>
</tr>
<tr>
<td>170412</td>
<td>2017-04-12</td>
<td>15:56:39.0</td>
<td>0.06</td>
<td>67.2%</td>
</tr>
<tr>
<td>170423</td>
<td>2017-04-23</td>
<td>12:10:45.0</td>
<td>0.086</td>
<td>45.2%</td>
</tr>
<tr>
<td>GW170608</td>
<td>2017-06-08</td>
<td>02:01:16.5</td>
<td>1</td>
<td>73.0%</td>
</tr>
<tr>
<td>170616</td>
<td>2017-06-16</td>
<td>19:47:20.8</td>
<td>$\ll 0.5$</td>
<td>66.2%</td>
</tr>
<tr>
<td>170630</td>
<td>2017-06-30</td>
<td>16:17:07.8</td>
<td>0.02</td>
<td>8.2%</td>
</tr>
<tr>
<td>170705</td>
<td>2017-07-05</td>
<td>08:45:16.3</td>
<td>0.012</td>
<td>26.3%</td>
</tr>
<tr>
<td>170720</td>
<td>2017-07-20</td>
<td>22:44:31.8</td>
<td>0.0097</td>
<td>48.2%</td>
</tr>
<tr>
<td>GW170729</td>
<td>2017-07-29</td>
<td>18:56:29.3</td>
<td>0.98</td>
<td>88.9%</td>
</tr>
<tr>
<td>GW170809</td>
<td>2017-08-09</td>
<td>08:28:21.8</td>
<td>1</td>
<td>73.9%</td>
</tr>
<tr>
<td>GW170814</td>
<td>2017-08-14</td>
<td>10:30:43.5</td>
<td>1</td>
<td>73.6%</td>
</tr>
<tr>
<td>GW170817</td>
<td>2017-08-17</td>
<td>12:41:04.4</td>
<td>1</td>
<td>100%</td>
</tr>
<tr>
<td>GW170818</td>
<td>2017-08-18</td>
<td>02:25:09.1</td>
<td>1</td>
<td>100%</td>
</tr>
<tr>
<td>GW170823</td>
<td>2017-08-23</td>
<td>13:13:58.5</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

senting spectrally hard, normal, and soft GRBs to generate expected photon counts from points evenly spaced across a 1° grid of the sky (Connaughton et al., 2015). The expected count rates are compared to the observed rates, and a $\chi^2$ minimization process identifies the most likely direction, with localization accuracy on the order
of degrees. GBM continuously takes data except during passage through the South Atlantic Anomaly (SAA) when the detectors are turned off due to high particle flux, yielding an uptime of approximately 85%.

GBM has developed increased sensitivity to weak, short GRBs by means of two offline searches: the Untargeted Search\(^2\) (Briggs et al., in prep.) and the Targeted Search (Blackburn et al., 2015; Goldstein et al., 2016a). These searches seek transient signals that do not exceed the high threshold set by the on-board triggering algorithms, and in this work, they are employed to find subthreshold gamma-rays coincident with the GW triggers in our search sample. Additional details on these searches follow.

### 4.2.2.1 Untargeted Search

The Untargeted Search is a blind search of continuous time-tagged event (CTTE) data, running automatically upon receipt of data from the *Fermi* spacecraft and using no information from GW searches. The search improves upon the onboard triggering algorithms by utilizing additional energy ranges and timescales, as well as a more sophisticated background-fitting model. Candidate events are required to have excess counts greater than 2.5\(\sigma\) relative to background in one detector and at least 1.25\(\sigma\) in a second detector. Significant candidates are autonomously distributed via the Gamma-ray Coordinates Network along with HEALPix skymaps to facilitate joint detections with other instruments (see e.g., Zhang et al. 2017). Further

\(^2\)https://gcn.gsfc.nasa.gov/fermi_gbm_subthresh_archive.html
details on the Untargeted Search and an analysis of its candidates will be published in a forthcoming article.

4.2.2.2 Targeted Search

The Targeted Search was designed for multi-messenger follow-up, requiring an input time and/or HEALPix skymap to seed a sensitive search of CTTE data. When seeking counterparts to GWs, the Targeted Search analyzes a 60 s window centered on the input GW time and searches timescales increasing by powers of 2 from 64 ms to 8.192 s, while phasing time bins by a factor of 4. Data from all 14 detectors are processed coherently to achieve a greater sensitivity to weak signals than when analyzing one detector at a time, as performed by the on-board flight software and the Untargeted Search. Three model spectra, described in Goldstein et al. (2016a), are folded through the detector responses to produce templates of expected counts which are then compared to the observed distribution of counts in each energy channel of each detector. The comparison is performed via a log-likelihood ratio ($\Lambda$), testing the alternative hypothesis of the presence of a signal with a similar spectrum versus the null hypothesis of only background noise. Treating $\Lambda$ as our detection statistic, the model spectrum resulting in the highest $\Lambda$ is selected as the preferred spectrum, and this procedure is repeated for each bin of data in the search (see Blackburn et al. 2015 for the detailed calculation of $\Lambda$). Bins contaminated by phosphorescent noise events are removed, and overlapping bins are merged to produce only the most significant bin. After this filtering, all remaining bins are retained as candidate events for our analysis. The different spectral templates tend to identify different types of sources.
in the GBM background, and such types may have very different rates of occurrence. To preserve sensitivity to these different sources, the bins are separated by best-fit spectral template, and event significance (i.e., FAR) is measured against background from the same template.

The Targeted Search was made more sensitive in preparation for O2 by improving the background estimation, revising the spectral template for hard GRBs, and implementing additional automated filters (Goldstein et al., 2016a). In particular, a Λ pre-filter was applied. The Λ calculation demands an initial estimation of the signal amplitude (effectively, the photon fluence in the time bin over 50-300 keV) that maximizes the likelihood of the hypothesis that a signal exists. The pre-filter excludes time bins with initial guesses of Λ < 5 from the full numerical optimization, increasing the speed of this computationally expensive task by up to a factor of 5. Bins with Λ < 5 have been verified to lie well within the GBM background, thus excluding them does not affect the sensitivity of the search. This updated version of the Targeted Search was used to analyze both the O1 and O2 triggers in our sample. Further improvements have been made for online analysis of CBC triggers during Advanced LIGO and Advanced Virgo’s third observing run (Goldstein et al., 2019), but were not used in this work.

4.3 Results

Here we present the results of our searches for gamma-ray counterparts to the GW triggers in our sample. To quantify event significance, each resulting search distribution is compared to that of background. The background used in the following
sections is composed of randomly selected times during which both LIGO detectors were in observing mode during O1 and O2. The ratio of random background between O1 and O2 is also roughly proportional to the LIGO/Virgo livetimes during O1 and O2. The same Targeted Search input parameters used for the search sample were used for the background, resulting in $\sim 10 \times 10^{-5}$ ($\sim 5 \times 10^{-6}$) Hz for Targeted Search analysis. Finally, the background times were chosen independently with respect to GBM and therefore include GBM trigger times.
4.3.1 GBM Trigger and Untargeted Search Results

As done in Burns et al. (2019), we first examine the time offsets between the search sample of CBC triggers and both GRBs detected by the GBM on-board flight software and subthreshold short GRB candidates from the Untargeted Search. This method is similar to the RAVEN analysis used by LIGO/Virgo (Urban, 2016). The Untargeted Search sample consists of all 187 candidates published during O1 and O2 via GCN, as described in the previous section. Combining these with the triggered GRBs, we obtained a total of 474 GRBs. The temporal offsets between the 25 GW events and the GBM GRBs were then determined, and the smallest offset for each GW candidate was taken. The search sample offsets are compared to those arising from random coincidences by finding the shortest temporal offsets between the background times and the GW trigger times. Both positive and negative offsets were allowed for search sample and background, but a maximum offset was not enforced. GW triggers occurring during Fermi passage through SAA were included, limiting the minimum time offsets for some GBM events; however the same treatment for the search was used for background.

The cumulative distribution for this search is presented in Figure 4.1. The search sample including GW170817 is shown with the solid gold line, while the distribution without GW170817 is displayed by the dashed brown line. Confidence regions were obtained empirically by Monte Carlo sampling of the background offset distribution with sample size equal to that of the search sample and finding the desired percentiles. The most significant deviation of the search distribution from that of ran-
Figure 4.2: O1 cumulative event rate distributions of the GBM background (black dashed lines) and search samples (solid gold line) for the GBM Targeted Search as a function of the log-likelihood ratio. Distributions are separated according to best-fitting spectral template. The transient GW150914-GBM is marked by a gold star in the hard template distribution.

dom background is caused by GRB 170817A, found $\sim$1.7 s after GW170817. Omitting GW170817, the shortest time interval between a CBC trigger from our sample and a GBM event is approximately 1000 s. On-axis prompt emission from a short GRB is not expected at such large time delays after a binary neutron star merger (Vedrenne and Atteia, 2009; Zhang, 2019), though larger delays may be allowed for off-axis emission (e.g., Salafia et al. 2018). Hence, with this first search we find no evidence for GW/gamma-ray associations apart from GW170817/GRB 170817A.
Figure 4.3: O2 cumulative event rate distributions of the GBM background (black dashed lines) and search samples (solid gold line) for the GBM Targeted Search as a function of the log-likelihood ratio. Distributions are separated according to best-fitting spectral template. Both the main peak and soft thermal tail of GRB 170817A, the short gamma-ray burst counterpart to GW170817, are indicated by gold stars in the normal and soft template distributions, respectively.

4.3.2 Targeted Search Results

The Targeted Search was used to search for subthreshold gamma-ray signals around 21 events from the CBC search sample. GBM data were not collected around triggers 161202, 161217, 170405, and GW170823 due to passage through the SAA; therefore these events were excluded from this search. For those remaining, the GBM coverage of the LIGO/Virgo localizations (see Table 4.1) was obtained. No LIGO/Virgo skymap was fully occulted by the Earth, and GBM observed between
\textasciitilde5\% and 100\% of the localization probability with an average observing fraction of 67.0\%.

The Targeted Search search follow-up distributions for O1 triggers and O2 triggers are shown as functions of \( \Lambda \) in Figure 4.2 and Figure 4.3, respectively. The background distributions were constructed by running the Targeted Search over the randomly selected times described above with the same parameters used for the search sample. As described in the previous section, confidence intervals for the search samples were produced by Monte Carlo sampling the background \( \Lambda \) distributions with the same sample size as the search sample. The distributions are separated into three categories according to the best-fitting spectral template, due to the different backgrounds affecting the three templates. Also, because of the time-variable nature of the background in each template, we obtain event significance by comparing the follow-up of O1 triggers to GBM background taken during O1 and O2 follow-up to O2 background.

For both O1 and O2, the search distributions lie largely within the 90\% confidence region of the median for all spectral templates. The O1 follow-up (Figure 4.2) does not show any significant outliers in the sample distributions. The transient GW150914-GBM is found with a FAR of \( 8.7 \times 10^{-4} \) Hz in the hard template distribution, where the FAR is the cumulative event rate of the background at the same \( \Lambda \), and lies just within 50\% confidence. The most significant event in the O2 follow-up (Figure 4.3) can be seen in the normal template distribution and is GRB 170817A, found with a FAR of \( 2.0 \times 10^{-5} \) Hz. The spectrally soft tail of GRB 170817A is also the most significant foreground event in the O2 soft template distribution, with a
FAR of $4.1 \times 10^{-4}$ Hz, but is within the 50% confidence region. No other significant candidates are found.

### 4.3.3 Targeted Search Joint Analysis

The FARs discussed in the previous section measure the significance of GBM transients with respect to the Targeted Search background only, regardless of the GW observations. Here we characterize the significance of coincidences between the GW events and the gamma-ray signals from the Targeted Search. In our previous works (e.g., Burns et al. 2019; Connaughton et al. 2016), this was done by ranking gamma-ray candidates by the Targeted Search FAR and the relative time offsets between the candidates and the GW triggers. We build upon these analyses by also considering (i) the probability that the GW signal is astrophysical in origin and (ii) the fraction of the LIGO/Virgo sky localization visible to GBM at the GW event time. Therefore, we rank gamma-ray candidates found by the Targeted Search with a statistic $R$ defined as

$$R = \frac{p_{\text{astro}} \times p_{\text{visible}}}{|\Delta t| \times \text{FAR}_{\text{GBM}}},$$

where $\Delta t$ is the time offset between the GW trigger and the gamma-ray event and $p_{\text{visible}}$ is the fraction of the LIGO/Virgo localization probability observable to GBM. A minimum offset of 64 ms was set to match the time binning of the data. GW triggers 151116 and 170616 were given the lowest $p_{\text{astro}}$ of the sample (i.e., 0.004) in light of the upper limits reported in GWTC-1 (see Table 4.1). Background events are ranked using the same statistic $R$. As background events have no corresponding
LIGO/Virgo information, skymaps and $p_{astro}$ values from the GW search sample were randomly assigned to each background event, and the fraction of GBM visibility was calculated at the background time using the randomly-selected skymap.

The ranking statistic of the search sample is mapped to a p-value, defined as the number of more highly ranked background events divided by the total number of background events, or $p_i = N(R > R_i)/N$, where $N$ is the number of gamma-ray events in the background and $i$ is the index of an event in the search sample. Again, search sample events from O1 and O2 are compared to background from O1 and O2, respectively. The cumulative distributions of the combined O1 and O2 p-values are shown in Figure 4.4, with and without GW170817 follow-up. The dashed black lines follow a uniform distribution, representing the null hypothesis that the search sample is consistent with that of background. The confidence regions for the p-value distribution were generated by random sampling of the background uniform distribution with sample size equal to the search sample size.

For the search including GW170817 follow-up, excesses of greater than $3\sigma$ are observed due to contributions from GRB 170817A. The main emission peak of GRB 170817A has a higher ranking than any other event in the background, making its p-value an upper limit. Removing all Targeted Search candidates associated with GW170817, excesses greater than $2\sigma$ are still observed. Contributing to this near the tail of the distribution is GW150914-GBM, which is found with a p-value of $\sim 1.8 \times 10^{-3}$. Of the remaining candidates (located around p-value = $1.0 \times 10^{-1}$), the detector lightcurves, spectral information, and localizations have been manually inspected. Real signals have consistent signal in detectors viewing approximately
Figure 4.4: Cumulative distribution of the Targeted Search p-values. The dashed black lines represent the expected background distribution. Left: Follow-up search sample including GW170817. The main emission episode of GRB 170817A is found with higher ranking than any other candidate within the background distribution. Its p-value is therefore marked as an upper limit (black triangle) at greater than 3σ deviation from the background p-value distribution. Right: Follow-up search sample without GW170817.

The same portion of the sky and are likely be found on multiple timescales by the Targeted Search. Short GRB-like signals typically display most of their emission above 50 keV. However, softer events with localizations consistent the Sun or the Galactic plane are likely to be solar flares or galactic sources rather than GRBs. All inspected events were judged to be either inconsistent with real short GRB-like signals or too weak in GBM data to constrain any properties. Therefore we judge this excess likely unrelated to the CBCs in the search sample. Some of the excess may be due to real but unrelated gamma-ray signals, and future observations can be used to either exclude or strengthen this feature. We do not find evidence here to report any associations other than GW170817 and GRB 170817A.
4.4 Summary and Future Directions

We have used LIGO/Virgo and *Fermi*-GBM data and multiple algorithms to search for gamma-ray transients associated with high and low significance CBC events reported in the first gravitational-wave transient catalog, GWTC-1. The GBM subthreshold searches for gamma-ray candidates employed improved algorithms to conduct more sensitive searches than those used in online follow-up during O1 and O2. All searches identified the coincidence between the short gamma-ray burst GRB 170817A and the BNS coalescence signal GW170817. We found no additional co-incident detections between CBC triggers and GBM triggers or Untargeted Search candidates. The GBM Targeted Search found the main emission peak and the long, soft tail of GRB 170817A with FARs of \(2 \times 10^{-5}\) Hz and \(4.1 \times 10^{-4}\) Hz, respectively, and the p-value of the joint association was found to deviate from the background distribution at greater than 3 sigma. The gamma-ray transient GW150914-GBM was also found with a FAR of \(8.7 \times 10^{-4}\) Hz, but was not a significant candidate on its own, lying just within the 50% confidence region of the hard spectral template. Future multi-messenger observations will be necessary to establish any astrophysical connection between gamma-ray emission and BBH mergers (see e.g., Veres et al. 2019). No other short GRB candidates were found in association with the CBC triggers.

In this work, the joint analysis was improved compared to that performed in Burns et al. (2019). In addition to the temporal offset and the Targeted Search FAR, we also considered the significance of the LIGO/Virgo trigger and the GBM visibility of the LIGO/Virgo sky localization. However, this analysis can be further
refined. By including all candidates reported in GWTC-1, we implicitly assumed that BBH, BNS, and NSBH (i.e., neutron star-black hole) mergers are equally likely to produce gamma-ray emission, and sought counterparts to these mergers using a wide parameter space of different timescales, energy ranges, and spectral templates. The broad nature of this search was motivated by the fact that, with only one confirmed coincidence, the observational properties of joint GW/GRB events are still largely unknown. Improving our search to target short GRB-like signals and filter transients from sources unrelated to CBCs, such as particle and galactic flares, may increase sensitivity to coincident, subthreshold short GRBs. Improvements in GBM search pipelines (Goldstein et al., 2019) and formal methodology (e.g., Ashton et al. 2018) are being undertaken for joint LIGO/Virgo and GBM analysis of CBC triggers from O3.
CHAPTER 5

CONCLUSION

GRBs are one of the most powerful and yet elusive objects in the Universe. In this dissertation, I report two studies of GRBs, motivated by the prospect of discovering more about their intrinsic properties and evolutionary patterns. First, a forward-folding method was developed to simulate GRBs from collapsar and BNS merger source populations, detect them based on the trigger capabilities of the *Fermi*-GBM instrument, and compare the distribution to GBM peak flux and luminosity data. It was found that the data are best-fit with a GRB population composed of \( \sim 45\% \) originating from BNS mergers, challenging the standard assumption that all long GRBs are produced by core-collapse supernovae and all short GRBs are formed by BNS mergers. However, the intrinsic properties of GRBs – particularly those from compact binary mergers – remain poorly understood. With the motivation to better constrain their sources properties and push to lower peak fluxes, I used the GBM subthreshold searches, the Targeted Search and the Untargeted Search, to search for GRBs coincident with GWs during the first and second gravitational wave observing runs (i.e., O1 and O2, respectively). The times and locations of candidate subthreshold GRBs were compared to those of GWs. No GW/GRB coincidences other than
GW170817/GRB 170817A were found, but the GBM subthreshold detection algorithm for weak short GRBs was improved, as well as the joint GW-GRB statistical formalism. Much remains to be discovered about GRBs, and with recent improvements in technology, the number of GRB redshift and progenitor detections should lead to tighter constraints on the source properties of GRBs, as well as the properties of their progenitors.
REFERENCES


107


Gwtc-3: Compact binary coalescences observed by LIGO and VIRGO during the second part of the third observing run. 2021e.


V. Connaughton, M. S. Briggs, A. Goldstein, C. A. Meegan, W. S. Paciesas, R. D. Preece, C. A. Wilson-Hodge, M. H. Gibby, J. Greiner, D. Gruber, P. Jenke,


124


A. D. Falcone, D. Morris, J. Racusin, G. Chincarini, A. Moretti, P. Romano, D. N. Burrows, C. Pagani, M. Stroh, D. Grupe, S. Campana, S. Covino, G. Tagliaferri,


A. Goldstein, C. Fletcher, P. Veres, M. S. Briggs, W. H. Cleveland, M. H. Gibby, C. M. Hui, E. Bissaldi, E. Burns, R. Hamburg, A. von Kienlin, D. Kocevski, B. Mailyan,


A. S. Pozanenko, P. Y. Minaev, S. A. Grebenev, and I. V. Chelovekov. Observation of the second LIGO/virgo event connected with a binary neutron star merger s190425z in the gamma-ray range. *Astronomy Letters*, 45(11):710–727,


144


V. V. Usov. Millisecond pulsars with extremely strong magnetic fields as a cosmological source of $\gamma$-ray bursts. , 357(6378):472–474, June 1992. doi: 10.1038/357472a0.


APPENDICES
APPENDIX A

NESTED SAMPLING

Nested sampling aims to estimate the evidence, $Z$, which is an $N$-dimensional integral over the parameter space. Rather than integrating over all dimensions directly, the nested sampling method re-factors $Z$ in terms of the prior volume $X$:

$$ Z = \int_0^1 L(X) \pi(X) dX $$

(A.1)

where

$$ X(L^*) = \int_{\mathcal{L} \geq L^*} \pi(\Theta) d\Theta $$

(A.2)

describes the region of the prior that has likelihood greater than or equal to $L^*$. The integration limits are determined so that when $L^* = 0$, the whole prior is included (i.e., $X = 1$), and as $L^* \to \infty$, smaller and smaller regions of the prior are considered (i.e., $X \to 0$). Thus, the evidence is evaluated by integrating over decreasing “nested” samples from the prior volume.

The nested sampling algorithm is described as follows. First, $N$ points are randomly sampled from the prior and the likelihood is evaluated at each point. These are known as live points. The live point with the lowest likelihood is discarded,
becoming the first dead point. Points are then randomly sampled from the prior until one is found that has a likelihood greater than that of the dead point. This process of discarding and replacing points with increasing likelihood is repeated until only a small fraction of the evidence remains. While the exact amount of remaining evidence is unknown, it can be estimated from each iterative group of live points:

$$\Delta Z_i \lesssim L_{\text{max}}^i X_i$$  \hspace{1cm} (A.3)

where $\Delta Z_i$ is the estimated remaining evidence at iteration $i$, $L_{\text{max}}^i$ is the maximum likelihood found within live points, and $X_i$ is the current size of the prior volume. It is common to terminate sampling when the ratio between the current evidence $Z_i$ determined by $N$ points:

$$Z_i \approx \sum_{k=1}^{N} L_k (X_{k-1} - X_k)$$  \hspace{1cm} (A.4)

and the remaining evidence $\Delta Z_i$ is small:

$$\Delta \ln Z_i \approx \ln (Z_i + \Delta Z_i) - \ln (Z_i) \leq 0.1$$  \hspace{1cm} (A.5)
APPENDIX B

POSTERIOR DISTRIBUTIONS FROM FITS TO SIMULATIONS

It is desirable to quantify the robustness of the method detailed in Chapter 3 by performing simulations. However, in this study, GRBs from collapsars and BNS mergers are tested separately, meaning the simulated data is composed of GRBs from only one source population. For each population, a luminosity function and rate density are chosen and $10^5$ GRBs are randomly drawn from these distributions. In addition to testing the rate densities from Section 3.3, the rate density from Wanderman and Piran (2010) is also tested for collapsar GRBs\(^1\). This rate is in the form of a simple broken power law, which follows the general form of the SFR but allows for more flexibility:

\[
R_{GRB}^{WP}(z) = \rho_0 \begin{cases} 
(1 + z)^{\alpha_C^z}, & z < z_C^z \\
(1 + z)^{\alpha_C^z - \beta_C^z}(1 + z)^{\beta_C^z}, & z > z_C^z
\end{cases}
\]

(B.1)

where $\alpha_C^z$ is the low redshift index, $\beta_C^z$ is the high redshift index, and $z_C^z$ is the break redshift. For the collapsar GRBs, I follow Lien et al. (2014) and inject model

\(^1\)This rate was not used in the main study as it has more parameters which yield increased computer runtimes.
parameters: $\rho_0^C = 0.4 \text{ Gpc}^{-3} \text{ yr}^{-1}$, $\alpha_L^C = -0.7$, $\beta_L^C = -3$, $L_{c,*}^C = 1 \times 10^{52} \text{ ergs s}^{-1}$, $z_1^C = 2$, $z_2^C = -0.7$, and $z_*^C = 3.5$. For the merger GRBs, I loosely follow Wanderman and Piran (2015) and set $\rho_0^M = 3.2 \text{ Gpc}^{-3} \text{ yr}^{-1}$, $\alpha_L^M = -0.5$, $\beta_L^M = -2.0$, and $L_{c,*}^M = 1 \times 10^{52} \text{ ergs s}^{-1}$. Following the methods outlined in Section 3.3 and Section 3.4, the injected model parameters are used to construct a simulated peak flux distribution. This simulated data is given as input to the nested sampling program, which yields posterior parameter distributions for the assumed models.

After running these simulations, another round of tests are performed where a luminosity distribution is also simulated and both the the peak flux and luminosity distributions are fit. Only luminosity functions $\Phi_{CPL}$ and $\Phi_{BPL}$ are tested in the second round since models with $\Phi_{SPL}$ are well-recovered in the first round. For collapsar GRBs, I assume there are 104 luminosity measurements in the GBM data sample, and for merger GRBs, I assume there are 7. This yields a combined number of 111 luminosity measurements, as used in Chapter 3.

The posterior plots for the first and second round of simulation tests are shown below (Figure B.2 – Figure B.16). The injected values are delineated in red, while the posterior medians and 90% confidence intervals (dashed lines) are printed above each 1-D histogram. The 2-D histograms display the 1-, 2-, and 3-$\sigma$ contours.

For the collapsar models, all injected values are found within 90% confidence (Figure B.2–Figure B.11). However, as the number of dimensions increases, the posterior distributions generally become less constraining. Models with the luminosity function $\Phi_{SPL}$ are well-recovered, with the injected values lying within the 1$\sigma$ confidence interval. Although the true GRB luminosity functions are likely more complex
than a simple power law, this illustrates how the peak flux distribution is a convolution of the rate density and the luminosity function: $\Phi_{SPL}$ has only 1 parameter (i.e., $\alpha_L^C$), and when it is constrained, constraints on the rate density become tighter. For fits to the peak flux data alone, the high-luminosity index, $\beta_L^C$, is not well-constrained (Figure B.5 and Figure B.10). This is expected since few GRBs occupy the high-end of the luminosity function and these GRBs tend to be detected at higher redshifts where the detection volume is large. Unfortunately, it is also increasingly difficult to detect these GRB since they tend to have smaller peak fluxes due to the distances involved. For similar reasons, the high-redshift index, $\beta_z^C$, is also not constrained for models with $R_{GRB}^{WP}$ and $\Phi_{CPL}/\Phi_{BPL}$. The cut-off/break luminosity $L_{c,*}^C$, on the other hand, remains relatively well-constrained regardless of the model. This is because increasing $L_{c,*}^C$ also increases the number of detectable GRBs, pushing the peak flux distribution to higher values and increasing its amplitude; vice versa for smaller values of $L_{c,*}^C$. In this way, the peak flux distribution is acutely sensitive to changes in $L_{c,*}^C$. When including luminosity observations, the parameters are significantly better constrained. While the high-redshift index $\beta_z^C$ remains unconstrained, the inclusion of a complete sample of redshift observations would likely improve this.

For the BNS merger models, the injected values are recovered only for the simplest model (i.e., $R_{GRB}^{BNS}$ and $\Phi_{SPL}$; Figure B.12). For models with luminosity functions $\Phi_{CPL}$ and $\Phi_{BPL}$, $L_{c,*}^C$ is found but the local rate $\rho_{0}^M$ and the low-luminosity index $\alpha_L^M$ are not (Figure B.13 and Figure B.15). Surprisingly, the high-luminosity index $\beta_L^M$ is recovered and well-constrained. This is because, given the luminosity functions $\Phi_{CPL}$ ($\Phi_{BPL}$), only $\sim 3\%$ ($\sim 8\%$) of the intrinsic distribution contributes
Figure B.1: Left: The simulated and detected 64-ms peak flux distributions obtained when assuming the rate density $R_{BNS,GRB}^{BNS}$ and the luminosity function $\Phi_{CPL}$ with parameter values stated in the text. Right: The associated simulated and detected luminosity distributions.

to the observed peak flux distribution (Figure B.1). Only the closest and brightest GRBs are detected, implying that the observed distribution is not strongly dependent on the amplitude of the intrinsic distribution or the low-luminosity index. Moreover, I find that fitting the luminosity distribution in addition to peak flux does not help to recover the injected parameters. The majority of the intrinsic luminosity distribution lies well below the GBM detection threshold, and the observable portion is too small to infer the true distribution. Essentially, the observed luminosity sample is incomplete.

In order to recover the injected parameters, it is necessary to decrease the peak flux detection limit. Indeed, when replacing the GBM detection probability curve with a peak flux threshold at $\sim 0.01$ ph cm$^{-2}$ s$^{-1}$, the injected values are recovered and well-constrained (Figure B.13). Thus, depending on the intrinsic distributions, the observed data may be incomplete and not informative enough to constrain the true parameters.
In summary, the simulation results demonstrate that if (1) the assumed luminosity function and rate density models reflect the intrinsic distributions, (2) the detection algorithm adequately represents GBM triggering, and (3) the data sample are complete, then the method outlined in Section 3.4.1 can successfully recover most parameters at the 90% confidence level. If a complete luminosity sample is included, the parameters will be even better constrained.
Figure B.2: Posterior probability distributions from assuming $\Phi_{SPL}$ and $R_{GRB}^{MF}$ and fitting the simulated 1-s peak flux distribution of GRBs from collapsars.

Figure B.3: Posterior probability distributions from assuming $\Phi_{CPL}$ and $R_{GRB}^{MF}$ and fitting the simulated 1-s peak flux distribution of GRBs from collapsars.
Figure B.4: Posterior probability distributions from assuming $\Phi_{CPL}$ and $P^{MF}_{GRB}$ and fitting the simulated 1-s peak flux and luminosity distributions of GRBs from collapsars.
Figure B.5: Posterior probability distributions from assuming $\Phi_{BPL}$ and $R_{GRB}^{MF}$ and fitting the simulated 1-s peak flux distribution of GRBs from collapsars.
Figure B.6: Posterior probability distributions from assuming $\Phi_{BPL}$ and $R_{GRB}^{MF}$ and fitting the simulated 1-s peak flux and luminosity distributions of GRBs from collapsars.
Figure B.7: Posterior probability distributions from assuming $\Phi_{SPL}$ and $P_{GRB}^{WP}$ and fitting the simulated 1-s peak flux distribution of GRBs from collapsars.
Figure B.8: Posterior probability distributions from assuming $\Phi_{CPL}$ and $R_{GRB}^{WP}$ and fitting the simulated 1-s peak flux distribution of GRBs from collapsars.
Figure B.9: Posterior probability distributions from assuming $\Phi_{CPL}$ and $R_{WP}$ and fitting the simulated 1-s peak flux and luminosity distributions of GRBs from collapsars.
**Figure B.10**: Posterior probability distributions from assuming $\Phi_{BPL}$ and $R_{GRB}^{WP}$ and fitting the simulated 1-s peak flux distribution of GRBs from collapsars.
Figure B.11: Posterior probability distributions from assuming $\Phi_{BPL}$ and $R_{GRB}^{WP}$ and fitting the simulated 1-s peak flux and luminosity distributions of GRBs from collapsars.
Figure B.12: Posterior probability distributions from assuming $\Phi_{SPL}$ and $R_{BNS}^{GRB}$ and fitting the simulated 1-s peak flux distribution of GRBs from BNS mergers.

Figure B.13: Posterior probability distributions from assuming $\Phi_{CPL}$ and $R_{BNS}^{GRB}$ and fitting the simulated 1-s peak flux distribution of GRBs from BNS mergers.
Figure B.14: Same as Figure B.13 but using a peak flux threshold of 0.01 ph cm$^{-2}$ s$^{-1}$. 
Figure B.15: Posterior probability distributions from assuming $\Phi_{BPL}$ and $R_{GRB}^{BNS}$ and fitting the simulated 1-s peak flux distribution of GRBs from BNS mergers.
Figure B.16: Same as Figure B.15 but using a peak flux threshold of 0.01 ph cm$^{-2}$ s$^{-1}$.