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学　位　論　文　概　要

Dissertation Summary

学位請求論文（Dissertation）
題名（Title）重力波同期イベントと類似した短時間ガンマ線バーストの系統的研究
*（邦訳又は英訳）（Title in Japanese or in English）*Systematic study of short gamma-ray bursts similar to gravitational wave events

専攻（Division）:数物科学専攻
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学位論文概要（Dissertation Summary）

Gamma-ray bursts (GRBs) are the most energetic electromagnetic explosions in the universe, releasing up to 10^{54} erg in a short duration. GRBs are classified into long GRBs (LGRB) with a duration of > 2 s and short GRBs (SGRB) with duration of ≤ 2 s. LGRB and SGRB are thought to have different origins. LGRB are explained by the collapse model of massive stars and have been confirmed by observations. On the other hand, SGRB are thought to originate from the merger of two compact objects, such as binary neutron star mergers or black hole-neutron star mergers, but lacked observational evidence for a long time.

On August 17, 2017, the gravitational wave interferometers Advanced LIGO and Advanced Virgo detected gravitational waves originating from a binary neutron star merger for the first time. Furthermore, ~ 1.7 s later, the gamma-ray space telescope Fermi observed a weak gamma-ray emission, which appeared to be SGRB, GRB 170817A. Additionally, follow-up observations across various wavelengths from ultraviolet to radio were conducted, and electromagnetic emission called kilonova, which is caused by radioactive decay of elements produced by the r-process, was also observed. The light curve of GRB 170817A obtained from Fermi/GBM reported the presence of a hard and short-duration component (hard spike) lasting ~0.5 s and a softer tail component (soft tail)

lasting about ∼2 s.

In this study, we have shown the following two points. (1) Soft tail emission associated with GRB 050709 can be explained by the cocoon emission. (2) We picked up known-redshift events similar to GRB 170817A among the SGRBs observed in Swift/BAT and examined the correlation between their peak energy Epeak and isotropic luminosity Liso. We then identified the average opening angles of the jets of the SGRBs.

(1) Burns et al.(2018) conducted an analysis of GRB 150101B, where the kilonova was observed, and reported emission with the hard spike and soft tail like GRB 170817A. GRB 050709, detected by the HETE-2 satellite, is the SGRB where the kilonova has been reported, similar to the two events previously mentioned. We have reanalyzed the data of this GRB, revealing the existence of a hard spike lasting approximately ∼0.2 s and a soft tail lasting about ∼0.3 s. Detailed temporal and spectral analysis suggests that this soft tail might be emission from a cocoon formed by the injection of energy into the surrounding material by a relativistic jet. The observed cocoon radius is estimated to be $\sim 10^{9}$ cm and the pressure $\sim 10^{19}$ erg cm−3 , consistent with the results of relativistic hydrodynamics simulations of binary neutron star mergers (Hamidani & Ioka 2021). We compared the physical parameters of this cocoon with those of other SGRBs. The relatively higher cocoon pressure and temperature in GRB 050709 may indicate a more on-axis jet compared to GRB 170817A and GRB 150101B.

(2) Previous studies have identified 12 events similar to GRB 170817A from Fermi data, based on the presence of the soft tail. However, most of these events lack redshift measurements, impeding the inference of their rest-frame properties. Here, we introduce a sample of 9 SGRBs from the Swift/BAT Gamma-Ray Burst Catalog (Figure 1). These events exhibit a soft tail resembling that of GRB 170817A and are accompanied by redshift measurements. Our analysis reveals a comparable distribution of the hard spike and soft tail of these events in the Epeak–Liso plane (Figure 2 (a)), suggesting potential similarities

in their origin in our SGRBs sample. Additionally, we investigate their average jet opening angle (θc) using the Epeak–Liso correlation, and consider its dependence on redshift (Figure (2) b). Employing a redshift-independent model, we found θc = 32.4 [−0.63, +0.63] degrees deviating from the average jet opening angle of ∼ 6 degrees derived from jet breaks. However, with a redshift-dependent model, our jet opening angles are overall comparable to those estimated from jet breaks.

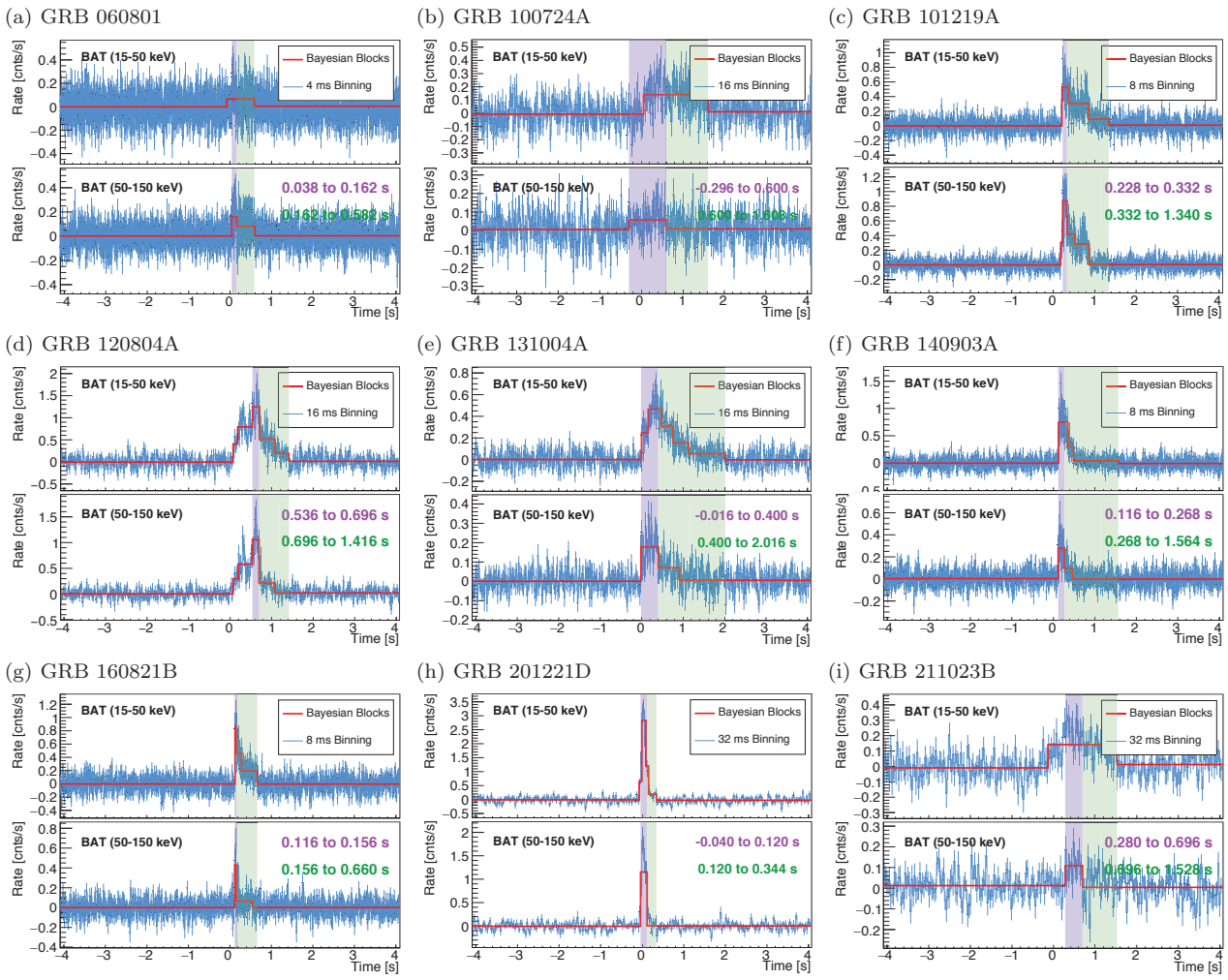
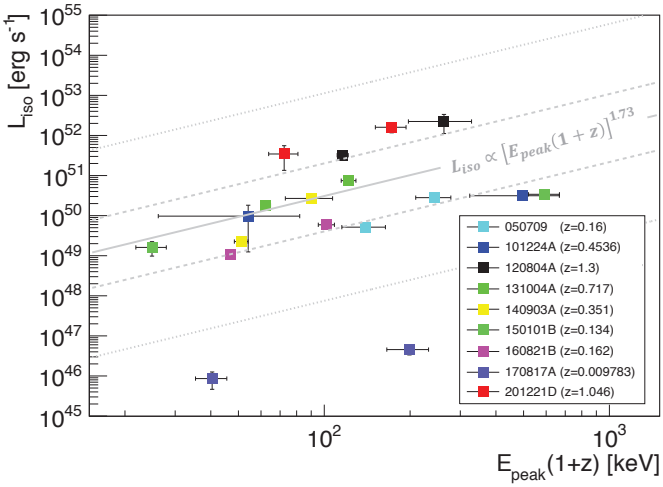


Figure 1 15–50keV (top panel) and 50–150keV (bottom panel) light curves detected by the Swift-BAT detector. The red lines represent the non-uniform bin light curves as determined by the bayesian block analysis. The brightest bin in the 50–150 keV count rate is defined as the hard spike (purple shaded region), and the subsequent time region is defined as the soft tail (green shaded region), for which spectral analysis was conducted.

(a) Golenetskii relation



(b) Norm $A(z)$ of each GRBs

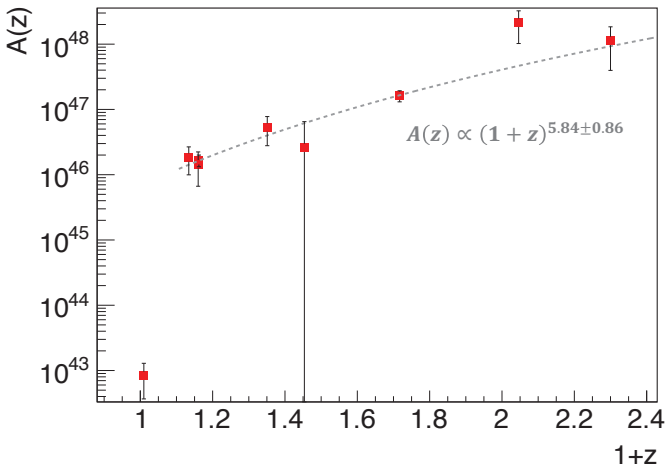


Figure 2 (a) Golenetskii relation plotted for events with Epeak of their hard spike and soft tail. The solid line is the result of the Yonetoku relation taken from Zhang et al. (2012), the dashed and dotted lines indicate 1σ and 3σ. (b) The norm *A(z)* of each GRB was obtained from (a) and correlated with the redshift.

令和　6年　2月　1日

学位論文審査報告書（甲）

1．学位論文題目（外国語の場合は和訳を付けること。）

重力波同期イベントと類似した短時間ガンマ線バーストの系統的研究

2．論文提出者　(1) 所　　属　数物科学　専攻

(2) 氏（ふり）　名（がな）　荻野（おぎの）　直樹（なおき）

3．審査結果の要旨（600～650字）

2017年に重力波と同期した短時間ガンマ線バースト(SGRB)が検出されたことで、電磁波以外の情報も含めて宇宙を包括的に理解するマルチメッセンジャー天文学が注目されている。荻野氏はこれまでに人工衛星で観測されたSGRBのデータを包括的に解析した。

SGRBの光度曲線に対してBayesian Block解析を適用することで、高エネルギーの短時間パルス(hard spike)とそれに続く低エネルギー放射(soft tail)が見られる重力波イベントと特徴が類似する9例のSGRBのスペクトル解析を行った。その結果、hard spikeとsoft tailは両方とも折れ曲がった冪関数で表すことが適切であり、重力波イベントに対して報告されている黒体放射では説明できないことを明瞭に示した。また、その時間変化がガンマ線バーストで良く知られているピークエネルギーと光度の相関関係によく合致し、物理メカニズムが同一であることを示すとともに、遠方のSGRBほど光度が高くなる傾向（光度進化）があることを発見した。

荻野氏は、この光度進化の起源を遠方のSGRBほど「明るくなる効果」と「放射ジェットが細く絞られる効果」に大別し、数値計算によりジェットの幾何学進化を推定した。具体的には、ジェット内部の光度がガウス分布に従うという一般的なモデルを仮定し、観測量である発生頻度、光度関数、個別の光度、光度進化を組み合わせた数値計算により、ジェットの開き角を求めるという新しい手法を開発し、最適解を求めた。その結果、光度進化の7割程度がジェットの幾何学進化に由来すると考えると、従来の観測結果と整合しつつ、荻野氏が発見した光度進化を物理的に説明できることを示した。この成果は、SGRBの発生メカニズムや宇宙論的進化の考察に影響を与える成果である。また、荻野氏が長年にわたって開発してきた観測機器を用いて、将来のマルチメッセンジャー天文学におけるSGRBの観測可能性を検討するなどの成果も盛り込んでいる。

以上の内容は学術的な新規性が高く、博士論文の内容として相応しいと判断できる。

4．審査結果　(1) 判　　定（いずれかに○印）　合　格　・　不合格

(2) 授与学位　　博　士（　理学　）