GRB 170817A/GW170817 is not a short gamma-ray burst, most likely an intermediate one

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Abstract GRB 170817A associated with the LIGO-Virgo GW170817 neutron-star merger event lacks the short duration and hard spectrum expected of a Short gamma-ray burst (GRB) from long-standing classification models. Classifying this burst correctly requires comparison with other GRBs detected by Fermi GBM. Our aim is to classify Fermi GRBs and test whether or not GRB 170817A belongs – as suggested – to the Short GRB class. The Fermi GBM catalog provides a large database with many measured variables that can be used to explore gamma-ray burst classification. We use statistical techniques to look for clustering in a sample of 1298 gamma-ray bursts described by duration and spectral hardness. Classification of the detected bursts shows that GRB 170817A belongs to the Intermediate, rather than the Short GRB class. GRB 170817A does not appear to fit into a simple phenomenological classification scheme. Recently, it was suggested that GRB 170817A/GW170817 may be a member of a new Short GRB sub-class. Here we show that this proposed sub-class is the Intermediate one, as discovered earlier.

Keywords Astronomical databases: miscellaneous \– Cosmology: miscellaneous \– Cosmology: observations \– Galaxies: high-redshift \– Gamma-ray burst: general \– Gamma-rays: general \– Methods: data analysis \– Methods: statistical

1 Introduction

One of the most exciting events in modern astrophysics has been the association of a gravitational wave coalescence event with a gamma-ray burst. On August 17, 2017, the LIGO and Virgo experiments (Abbott et al. 2017) observed a chirp (GW170817) associated with the merger of two compact objects in the mass range $1.17 - 1.60$ $M_\odot$ and a combined mass of $2.74^{+0.004}_{-0.001}$ $M_\odot$. The LIGO/Virgo chirp is consistent with merging neutron stars of GRB 170817A triggered by the Fermi Gamma-ray Burst Monitor (GBM) experiment (Connaughton et al. 2017) 1.7 s later. Preliminary properties identified for the GBM trigger (Goldstein et al. 2017; Goldstein et al. 2017) were a duration of $\approx 2$ s and a 64 ms peak flux of $3.7 \pm 0.9$ ph/s/cm$^2$ (10 – 1000 keV).

At first glance, the association of the lower mass LIGO event with a Short GRB seems to validate standard theoretical models based on known GRB classification. Evidence from the 1980’s suggested that two GRB classes existed on the basis of duration [Mazets et al. 1981, Norris et al. 1984]. Subsequent observations provided by the Burst And Transient Source Experiment (BATSE) supported this division [Kouveliotou et al. 1993, Koshut et al. 1996] and also found the Short GRBs to have harder spectra than the Long ones. Compact objects are needed to produce large GRB luminosities and short timescales, and the BATSE duration bimodality seemed to point to the existence of two distinctly different GRB populations. It was felt that although the timescale of massive star core-collapse was sufficient to explain Long GRBs, it was too long to explain Short GRBs. As a result, theoretical models
constraining progenitor compactness were merged with observational evidence of clustered GRB properties to develop expectations of class properties.

For decades astronomers have sought clear additional evidence that Short GRBs differ from Long GRBs other than by duration and spectral hardness (Norris et al. 2001; Balázs et al. 2003; Zhang et al. 2003; Lu & Liang 2010; Li et al. 2010). Some low-luminosity Long GRBs have been associated with Type Ic supernovae (SN) (Hjorth et al. 2003; Campana et al. 2006; Pian et al. 2006; Blanchard et al. 2016), supporting the idea that the Long GRBs in general are related to deaths of massive stars (Woosley 1993; Paczyński 1998; Woosley & Bloom 2006; Blanchard et al. 2016). For Short GRBs, the absence of SN associations, the location of GRBs in metal-poor regions, and their lower luminosities disfavor a massive star origin and point to compact binary mergers (Paczyński 1986; Usov 1992; Berger 2014). Observations supportive of these differences have included GRB luminosities, different host galaxies and redshift distributions (Berger 2014; Levan et al. 2010), the metallicity of the environment surrounding the GRB, different afterglow properties, etc. Thus, these supportive observations have led observers to believe that the identification of a Short GRB with gravitational wave evidence of a neutron star-neutron star merger would unambiguously demonstrate the correctness of the standard model.

Despite the clear association of GRB 170817A with GW170817, the burst’s duration, fluence, and soft spectrum allow for an uncomfortable ambiguity in its interpretation as a Short GRB. It is not clear that this object is either a Long or a Short GRB, as its properties straddle the boundary between the two classes. Most formal statistical classification techniques find at least one other class (the Intermediate class) occupying the space between the Long and Short GRB classes, although more statistical clusters have also been found.

Using multi- and uni-variate statistical analysis techniques, Mukherjee et al. (1998) and Horváth (1998) found evidence for a third GRB class in data from the Third BATSE Catalog (Meegan et al. 1996). The class is composed of GRBs having intermediate durations (2 s ≤ T_{90} ≤ 10 s), intermediate fluences, and soft spectra characterized by soft hardness ratios. Many authors (Hakkila et al. 2001; Balastegui et al. 2001; Rajaniemi & Mähtönen 2002; Horváth 2002; Hakkila et al. 2002; Boronov & Horváth 2004; Horváth et al. 2006; Chattopadhayay & Veres 2007; Zitouni et al. 2017) have since confirmed the existence of this Intermediate GRB class in the same database using statistical techniques and/or data mining algorithms. The Intermediate class has also been found in the Beppo-SAX (Horváth 2009) and Swift data (Horváth et al. 2008; Huia et al. 2009; Horváth et al. 2010; Horváth & Tóth 2016), even though Beppo-SAX had a smaller effective area than BATSE, and Swift works in a different energy range. The properties of each class differ depending on instrumental characteristics of the experiment measuring them, the classification attributes being used, the classification techniques being applied, and the sample size. Through these analyses, class properties have been found to differ somewhat (the Short-Intermediate division typically occurs at longer durations for experiments other than BATSE), and the Short-Intermediate division has been found to be more robust than the Intermediate-Long division.

The T_{90,BATSE} ≈ 2 s boundary separating Long and Short GRBs is not robust for a variety of reasons. First of all, it has been defined from GRBs observed by a single instrument (BATSE) having its own surface area, spectral response, temporal resolution, and angular sensitivity. Second, it has been defined from a bimodal interpretation of one specific dataset (defined in Kouveliotou et al. 1993). Third, acceptance of this division has been based partially on theoretical models rather than entirely on observational ones. Much of the GRB literature has incorrectly painted classification as a black-and-white division separating two distinctly different types of progenitors, whereas it is in reality a gray area occupied by observations of one distinct observational class (the Short class) separated in duration, fluence, and spectral hardness from at least one other (the Long class). As a result, the 2 s bimodal classification scheme should not be seen as being applicable to all GRB data, and especially not to data collected by GRB instruments other than BATSE. Instead, classification of GRBs collected by a specific instrument should be done independently, and interpretation should subsequently proceed based solely on observational evidence rather than on theoretical models. Classification is a meaningful way to regard data, but not theories.

Published statistical clustering analyses have used a variety of different variables in their classification approaches: duration information (Horváth 1998; Balastegui et al. 2001; Rajaniemi & Mähtönen 2002; Horváth 2002; Horváth et al. 2008; Huia et al. 2009; Horváth 2009; Zitouni et al. 2015; Tarnopolski 2015a,b; Horváth & Tóth 2016; Tarnopolski 2016; Kulkarni & Desai 2017), duration and hardness (Horváth et al. 2004; 2006; Veres et al. 2010; Horváth et al. 2010; Koen & Benjamin 2012; Jin et al. 2013; Tsutsui & Shigeyama 2014; Shalimov & Nemiroff 2014; Rípa & Mézáros 2015; Yang et al. 2016; Zhang et al. 2016), or more than two variables (Mukherjee et al. 1998; Hakkila et al. 2003; Chattopadhayay et al. 2007; Kann et al. 2011; Lü et al. 2014; Li et al. 2016; Modak et al. 2017; Chattopadhayay & Maitra 2017).
In this paper we only use duration and spectral hardness to examine classification of the very interesting GRB 170817A, because we intended to fit this event into the scheme of our former analyses. While trying to explain the observed peculiarities of the high energy emission of GRB 170817A, Bégué et al. (2017) speculate that it might represent a new (short) GRB subclass.

The paper is organized as follows. In Sect. 2 we present the cluster analysis of the Fermi data, Sect. 3 discusses the results, and Sect. 4 provides the summary and outlook.

2 Cluster analysis with duration and hardness

On September 12, 2017, the Fermi GBM Catalog[1] contained 2055 GRBs for which spectral fits were available, and listed more than 300 parameters for those. For our analysis we have chosen to use the duration ($T_{90}$) and the hardness variables. The spectral hardesses used here have been kindly provided by Drs. Bhat and Veres (as also used in Goldstein et al. 2017).

To improve the data quality we excluded GRBs having poorly-measured hardesses. In order to retain as many GRBs in the sample as possible while still minimizing the number of bursts with poor hardness measurements, we chose to exclude 79 GRBs having hardness uncertainties that are bigger than 1.5 times of the hardness measurement. This leaves us with 1298 GRBs for our analysis.

Our analysis is made using the \textit{mclust} \cite{Fraley2002,Fraley2012} package in the R environment \cite{RCoreTeam2013}. The first step is to see whether there are any outliers in the 1298-element dataset, using hardness and duration as our classification variables. For this purpose the \textit{HDoutliers} package \cite{Fraley2016} was used and no outlier was found.

We then proceeded to identify the optimal number of classes in the hardness vs. duration parameter space using the Bayesian Information Criterion (BIC). The BIC value was calculated using the \textit{Mclust()} function, initially assuming N = 1 \ldots 10 groups for all the models available (Fig. 1). The largest BIC value of −2502.29 was obtained using the EEE model (assuming clusters having ellipsoidal distributions described by equal volumes, shapes and orientations) assuming three classes.

The \textit{Mclust()} function also returns the probabilities $p_{Si}$, $p_{II}$, and $p_{Li}$ that burst $i$ belongs to the Short (S), the Intermediate (I), or the Long (L) classes, respectively. The assignment of each GRB according to the maximal $p_{ki}$ values gives the grouping plotted in Fig. 2. By summing these probabilities one gets $p_S = \sum_i p_{Si} = 170.58$, $p_I = \sum_i p_{II} = 130.21$, and $p_L = \sum_i p_{Li} = 997.21$.

![Fig. 1 The optimal BIC value prefers three classes with EEE method (clusters having ellipsoidal distributions described by equal volumes, shapes and orientations).](https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html)

The Intermediate class can clearly be seen between the Long and Short GRB classes having the softest spectral hardness (Fig. 2). The general characteristics of the groups are similar to those of BATSE (Horváth 1998, Mukherjee et al. 1998) and Swift (Horváth et al. 2008, Veres et al. 2010, Horváth et al. 2010).

Based on its duration and hardness, GRB 170817A/GW170817 belongs to the Intermediate class ($p_{L,GW} = 58.3\%$ against $p_{S,GW} = 16.5\%$ and $p_{L,GW} = 25.2\%$).

3 Discussion

The properties of the Intermediate GRB class are fuzzy because of the overlap of the groups. It is also strongly dependent on the instrumental characteristics, therefore the classification should be done separately for each orbital experiment. This misapplication of GRB classification schemes has resulted in ambiguity that has, up until now, been ignored.

Koen & Bered (2012) analyzed GRB classes from the Swift BAT data and concluded that two classes sufficiently describe the spectral hardness distribution, whereas three components are needed to characterize the duration distribution. The Intermediate class identified by Koen & Bered (2012) has durations of around 3 \ldots 20 seconds, which is in a good agreement with Horváth & Tóth (2010) who find the Intermediate class durations to be in the 4 to 30 second range. We note here that Koen & Bered (2012) assumed that the distribution is a combination of Gaussians, which assumption is supported by Ioka & Nakamura (2002).

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[1]: https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html
In addition to Swift, instrumental effects might also be responsible for affecting Fermi classification results. Qin et al. (2013) analyzed the data of 315 Fermi GRBs, studying the dependence of the duration distribution on energy and on various instrumental and selection effects. They have suggested that the true durations of a GRB could be much longer than that is observed.

Fig. 2 The log($T_{90}$) - log(HR) distributions of the three classes. The Short GRB class is shown in blue, the Intermediate GRBs in green, and the Long GRBs in red. The GRB 170817A is clearly in the Intermediate group region.

4 Summary and outlook

GRB 170817A/GW170817 has been unambiguously identified as resulting from merging neutron stars. However, GRB 170817A’s soft spectrum, intermediate duration, and unexpectedly faint luminosity do not appear to agree with the standard model.

Over the years many references to GRB classification have unfortunately devolved into an oversimplified and non-rigorous treatment based on a theoretical preference for only two GRB classes (Long and Short) separated using instrumental-dependent rules deduced from data provided by one de-orbited instrument (BATSE). In order to resolve the ambiguity of GRB 170817A’s class membership, we classified GRBs by applying statistical clustering methods to bursts observed by Fermi’s GBM, the same instrument that detected GRB 170817A.

The classification scheme applied to 1298 Fermi GRBs using duration $T_{90}$ and spectral hardness data. The choice of the classification parameters and the assumptions about how GRBs cluster in this parameter space lead to three classes, which are easily identified as Long, Short, and Intermediate ones. GRB 170817A/GW170817 is unambiguously identified as an Intermediate burst.

We conclude therefore that GRB 170817A represents an Intermediate GRB resulting from a neutron star-neutron star merger. This is inconsistent with the standard model: either Intermediate GRBs must be physically very different from Long GRBs even though their observational properties overlap, or Intermediate GRBs and recognition of the existence of the Intermediate GRB class.

Our classification evidence suggests that GRB 170817A represents an Intermediate GRB rather than a peculiar Short GRB. If we accept our classification results along with the evidence from the gravitational wave chirp, then Intermediate GRBs appear to be associated with compact merger systems.
must be observationally very different from Short GRBs even though they are thought to originate from similar progenitors. Béguel et al. (2017) have recently explored different emission mechanisms to explain the unusually weak prompt emission of GRB 170817A, assuming it is a Short GRB. They find that synchrotron self-Compton emission from a structured jet might explain the burst’s soft and low-luminosity characteristics. If true, then this explanation would indicate that the mechanism producing this kind of merger differs from previously accepted mechanisms for Short GRBs. Accordingly, Béguel et al. (2017) suggested that GRB 170817A was a member of a new Short GRB sub-class. Here we show that their proposed subclass is more likely to be the Intermediate one, as earlier discovered by Horváth (1998) and Mukherjee et al. (1998).

More observations of this type of system are clearly needed, especially by instruments having larger surface areas and greater sensitivity at lower energies (e.g., Swift). Further studies will investigate how many such events we may expect to detect.

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