Classifying GRB 170817A/GW170817 in a Fermi duration - hardness plane

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Abstract GRB 170817A, associated with the LIGO-Virgo GW170817 neutron-star merger event, lacks the short duration and hard spectrum of a Short gamma-ray burst (GRB) expected from long-standing classification models. Correctly identifying the class to which this burst belongs requires comparison with other GRBs detected by the Fermi GBM. The aim of our analysis is to classify Fermi GRBs and to 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 most likely belongs to the Intermediate, rather than the Short GRB class. We discuss this result in light of theoretical neutron-star merger models and existing GRB classification schemes. It appears that GRB classification schemes may not yet be linked to appropriate theoretical models, and that theoretical models may not yet adequately account for known GRB class properties. We conclude that GRB 170817A may not fit into a simple phenomenological classification scheme.

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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 $1.17 - 1.60\ M_\odot$ with a combined mass of $2.74^{+0.004}_{-0.001}\ M_\odot$. The LIGO/Virgo chirp is thus consistent with merging neutron stars. GRB 170817A triggered the Fermi Gamma-ray Burst Monitor (GBM) experiment (Connaughton et al. 2017) 1.7 s after the gravitational wave event. Preliminary properties identified the GBM trigger (Goldstein et al. 2017; Goldstein et al. 2017) as having a duration of ≈ 2 s and a 64 ms peak flux of 3.7 ± 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. 2009; Lu & Liang 2010; Li et al. 2016). 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 these events in metal-poor regions, and their lower luminosities disfavor a massive star origin and point to compact binary mergers (Paczynski 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. 2016), 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 $\leq$ T_{90} $\leq$ 10 s), intermediate fluences, and soft spectra characterized by soft hardness ratios. Many authors (Hakkila et al. 2000; Balastegui et al. 2001; Rajaniemi & Mähönen 2002; Horváth 2002; Hakkila et al. 2003; Borgonovo 2004; Horváth et al. 2006; Chattopadhyay et al. 2007; Zitouni et al. 2015) 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; Huja 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 (de Ugarte Postigo et al. 2011).

The $T_{90,\mathrm{BATSE}} \approx 2$ 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 & Mähönen 2002; Horváth 2002; Horváth et al. 2008; Huja 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 & Bere

2012; Qin et al. 2013; Tsutsui & Shigeyama 2014; Shahmor 2015; Řípa & Mészáros 2016; Yang et al. 2016; Zhang et al 2016), or more than two variables (Mukherjee et al. 1998; Hakkila et al. 2003; Chattopadhyay et al. 2007; Kann et al. 2011; Lü et al. 2014; Li et al. 2016; Modak et a 2017; Chattopadhyay & 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 prior 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 sub-class.

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 hardness variables. The spectral hardnesses 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 have excluded GRBs having poorly-measured hardnesses. 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 larger than 1.5 times the hardness measurement. This leaves us with 1298 GRBs for our analysis.

Our analysis is made using the *mclust* (Fraley & Raftery 2002; Fraley et al. 2012) package in the R environment (R Core Team 2015). 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 *HDoutliers* package (Fraley 2016) was used and no outliers were 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 *Mclust()* function, initially assuming $\mathrm{N} = 1 \ldots 10$ groups for all the models available (Fig. 1). The largest BIC value of -2502.29 was obtained using the EEE model (assuming clusters having elliposidal distributions described by equal volumes, shapes and orientations) assuming three classes.

[1]https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html

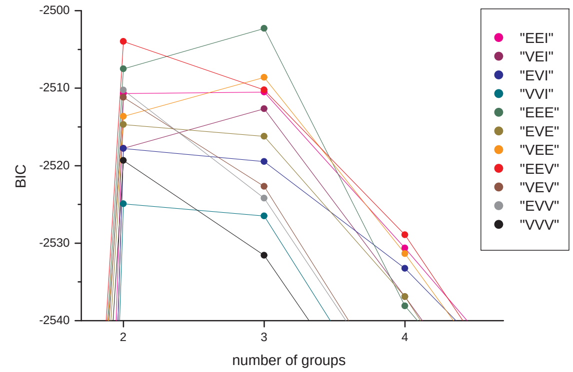

Fig. 1 The optimal BIC value prefers three classes with EEE method (clusters having elliposidal distributions described by equal volumes, shapes and orientations).

The *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 $p_L = \sum_i p_{Li} = 997.21$.

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 found in BATSE (Horváth 1998; Mukherjee et al. 1998) and Swift (Horváth et al. 2008; Veres et al. 2010; Horváth et al. 2010) data.

Based on its duration and hardness, GRB 170817A/GW170817 belongs to the Intermediate class ($p_{I,GW} = 58.3\%$ against $p_{S,GW} = 16.5\%$ and $p_{L,GW} = 25.2\%$). On the other hand, one can check the hypothesis that GRB 170817A is a Short GRB. Using the Fermi Short group parameters (see Table 1.) and the position of the GRB 170817A in the duration - hardness plane, classification of GRB 170817A as a Short burst results in a misclassification probability 94.0%, which is near the two sigma limit.

3 Discussion

The properties of the Intermediate GRB class are fuzzy because class properties overlap one another in the chosen parameter space. The choice of classification parameters is generally based on what an instrument measures, rather than on an idealized yet unknown parameter that might more clearly aid in class delineation. The

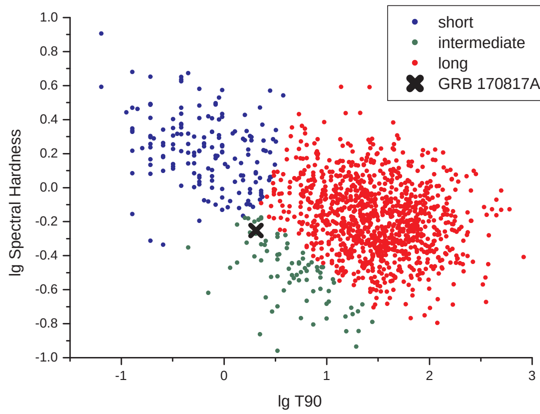

Fig. 2 The log(T_{90}) - log(HR) distributions of the three classes. The Short GRB class is shown in blue, the Intermediate GRB class is in green, and the Long GRB class is in red. GRB 170817A is clearly located in the Intermediate group region.

measured parameters and their corresponding measurement uncertainties strongly depend on the instrumental characteristics and sampling biases. As a result, classification is instrument-dependent and should be done separately for each orbital experiment. This misapplication of GRB classification schemes has resulted in ambiguities that have, up until now, been ignored.

Koen & Bere (2012) classified Swift BAT GRBs and concluded that three classes are needed to characterize the duration distribution, whereas only two are are required to sufficiently describe the spectral hardness distribution. Swift's lower-energy spectral response is likely responsible for weakening spectral hardness as a classification attribute: high-energy emission is important in delineating BATSE classes. The Intermediate class identified by Koen & Bere (2012) has durations of around $3 - 20$ seconds, which is in good agreement with (Horváth & Tóth 2016) who find the Intermediate class durations to be in the $4 - 30$-second range. We

Table 1 Parameters for the best fitted three groups. w is the weight of the group.

	$center(logT_{90})$	$logHR$	w
short	-0.124	0.213	0.129
intermediate	0.906	-0.404	0.062
long	1.488	-0.175	0.809

note here that Koen & Bere (2012) assumed that the distribution is a combination of Gaussians, which is an assumption supported by Ioka & Nakamura (2002).

In addition to Swift, instrumental effects might also be responsible for affecting Fermi classification results. Qin et al. (2013) analyzed 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 what is observed.

Analyses of data from a variety of orbital high-energy satellites continue to find evidence for three GRB classes over two. Tsutsui et al. (2009, 2013); Tsutsui & Shigeyama (2014) have used data from several orbital instruments, as well as X-ray and optical afterglow data, to study GRB classes, and have found a third group with durations of $T_{90,BAT} \approx 5$ s. Zitouni et al. (2015) has analyzed the CGRO/BATSE and Swift/BAT GRB data to find a very similar class structure to Horváth (2002).

Although most rigorous GRB classification studies find three classes in the data, there have been exceptions. In a recent publication, Tarnopolski (2015b) proposes that the division between Short and Long bursts corresponds to a T_{90} of 3.4 seconds rather than two seconds. Tarnopolski (2015a) analyzed the Fermi GBM duration data of 1566 GRBs. Although he found a third component in the distribution, the significance was not convincing. This may be due to methodology: the binned data were tested with a χ^2 fit rather than using a maximum likehood method and unbinned data. This points to an additional difficulty that has been found in applying statistical clustering techniques: the results depend on heuristic assumptions about the form that clustering takes and on the techniques most likely to extract this assumed clustering.

Although the three identified Fermi GBM classes of GRB overlap, GRB 170817A's prompt characteristics indicate that it is most likely an Intermediate GRB rather than a Short one (being a short GRB has only 6% probability). Association of a LIGO chirp with an Intermediate GRB is itself inconvenient in that it requires modification of existing theoretical models as well as recognition of the existence of the Intermediate GRB class.

Our classification evidence suggests that GRB 170817A represents an Intermediate GRB rather than an outlier Short GRB. Accepting these classification results along with the evidence from the gravitational wave chirp suggests that Intermediate GRBs are associated with compact merger systems, If Intermediate GRBs are somehow an extension of the Short GRB merger model, then a more thorough characterization of Intermediate

GRB afterglow and host galaxy properties need to be made in order to determine how they differ from those of traditional Short GRBs. de Ugarte Postigo et al. (2011) concluded that the intermediate bursts are found to be less energetic and have dimmer afterglows than long GRBs, especially when considering the X-ray light curves, which are on average one order of magnitude fainter than long bursts. There is a less significant trend in the redshift distribution that places intermediate bursts closer than long bursts. Except for this, intermediate bursts show similar properties to long bursts. In particular, they follow the E_{peak} versus E_{iso} correlation and have, on average, positive spectral lags with a distribution similar to that of long bursts. As for long GRBs, they normally have an associated supernova, although some intermediate bursts have been found to contain no supernova component.

It is still possible that GRB 170817A is an outlier Short GRB, which would be more consistent with the statistical properties of Short and Intermediate GRBs. Besides sharing more parameter space with the Longs than with the Shorts, Intermediates extend a correlation found in Long GRBs where fainter Longs are softer than brighter Longs (*e.g.* Hakkila & Preece (2011)). Pulses of all GRB classes exhibit fairly similar triple-peaked structures (Hakkila & Preece 2014; Hakkila et al. 2015, 2018), suggesting that a common mechanism is responsible for producing them regardless of their progenitors and/or host galaxies. However, pulses produced by both Long and Intermediate GRBs appear to have significantly longer durations than pulses from Short GRBs (Hakkila & Preece 2014; Hakkila et al. 2018).

The growing number of bursts detected by the Fermi GBM provides additional data on which GRB classification schemes can be tested. GBM has a spectral energy response that is similar to, but broader, than BATSE, and a surface area that is smaller than that of BATSE. Given the complementary, yet different, characteristics of the Fermi GBM instrument to BATSE, Swift, and Beppo-SAX, the application of these statistical clustering techniques to explore GRB classification is the subject of forthcoming studies.

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 of Short GRBs.

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 leads to three classes, which are easily identified as Long, Short, and Intermediate ones. GRB 170817A/GW170817 is most probably identified as an Intermediate burst.

We conclude 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 must be observationally very different from Short GRBs even if they to originate from similar progenitors.

Bégué et al. (2017) have recently explored different emission mechanisms to explain the unusually weak prompt emission of GRB 170817A, assuming it to be 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, Bégué 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).

Relativistic 2D and 3D MHD numerical simulation models have also been developed to explain the low-luminosity, 2s duration, and hard-to-soft prompt spectrum of GRB 170817A (Kasliwal et al. 2017; Gottliebet al. 2018; Bromberget al. 2017). Several of these models involve a mildly relativistic shock breakout resulting from an asymmetric jet interacting with the previously expelled merger ejecta. The low luminosity, hard-to-soft prompt $\gamma-$ emission is explained by the jet breakout emanating from a wide-angle, mildly-relativistic cocoon. The models commonly assume that a special model is needed to explain the low luminosity and possibly multicomponent hard-to-soft prompt spectrum, and that these characteristics are somehow linked. However, hard-to-soft multicomponent prompt spectral evolution is a ubiquitous feature not only of all Short GRB pulses Hakkila et al. (2018) but of all GRB pulses (Hakkila & Preece 2014; Hakkila et al. 2015), regardless of duration and including Intermediate GRBs. MHD models may thus need to be generalized to explain why all GRBs exhibit this behavior, rather than attributing it to specific characteristics of an individual GRB.

Other authors also favor the idea that GRB 170817A's low luminosity and soft spectra are produced by a structured jet. Meng et al. (2018) demonstrate that the soft spectrum of GRB 170817A is consistent both with a two-component model in which the spectrum is softened by photospheric emission produced in the structured jet and with synchrotron emission produced in an optically-thin region. From afterglow observations, Margutti et al. (2018) find support for the different cases of a mildly relativistic spherical ejecta and a structured jet viewed off-axis. Troja et al. (2018) use broadband observations to demonstrate that Gaussian jet and re-energized cocoon models are favored over models involving homogeneous jets, power-law jets, and simple spherical cocoons. Lazzati et al. (2017) combine numerical simulations with afterglow observations to demonstrate that the observed prompt and afterglow characteristics of GRB 170817A can be explained by either a structured jet afterglow or a radially stratified spherical fireball. Zhang et al. (2017) suggest that structured jets might also explain other faint, soft GRBs found in the Fermi data archive. This suggestion provides implicit support that structured jets produced in some merging neutron star systems might be related to an Intermediate GRB class.

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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