ARE ULTRA-LONG GAMMA-RAY BURSTS DIFFERENT?

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ABSTRACT

The discovery of a number of gamma-ray bursts (GRBs) with duration exceeding 1000 s has opened the debate on whether these bursts form a new class of sources, the so-called ultra-long GRBs, or if they are rather the tail of the distribution of the standard long GRB duration. Using the long GRB sample detected by Swift, we investigate the statistical properties of long GRBs and compare them with the ultra-long burst properties. We compute the burst duration of long GRBs using the start epoch of the so-called “steep decay” phase detected with Swift/XRT. We discuss also the differences observed in their spectral properties. We find that ultra-long GRBs are statistically different from the standard long GRBs with typical burst duration less than 100–500 s, for which a Wolf–Rayet star progenitor is usually invoked. Together with the presence of a thermal emission component we interpret this result as indication that the usual long GRB progenitor scenario cannot explain the extreme duration of ultra-long GRBs, their energetics, as well as the mass reservoir and size that can feed the central engine for such a long time.

Key word: gamma-ray burst: general

Supporting material: machine-readable table

1. INTRODUCTION

Gamma-ray bursts (GRBs) are among the most extreme events in the universe (see the review by Meszaros 2006). The distribution of their duration is very broad, as they can last from a few milliseconds to several hundreds of seconds (see for instance Kouveliotou et al. 1993). Despite these events presenting extreme diversity in duration (spanning about six decades), variability (four decades), energy span (eight decades when considering the afterglow phase), and peak energy (two decades), so far they have been categorized in only two classes (Dezalay et al. 1992; Kouveliotou et al. 1993). This classification is based on both their temporal and spectral statistical properties. It is this categorization that led to further studies such as the localization of the events with respect to the host galaxy (e.g., Fong & Berger 2013), which points toward different progenitor natures; a binary system of neutron stars (Eichler et al. 1989) for the short GRBs (hereafter sGRBs) and a collapsar (Woosley 1993) for the long GRBs (hereafter lGRBs). Though finding categories in a phenomenon does not necessarily imply different natures, this approach often leads to advances in its comprehension: a typical example is the unified model of active galactic nuclei (AGNs; see Antonucci 1993, for a review) that was able to explain in a coherent way the various manifestations of AGNs, such as Seyfert I, II, III, BL Lac, radio loud galaxies, etc.

The collapsar model has been proposed to explain the amount of energy needed for an IGRB to be produced, and it has been effective in explaining several properties of these sources: e.g., the presence of a supernova (Hjorth et al. 2003; Stanek et al. 2003) or the observation of stellar winds around the burst source (Gendre et al. 2004, 2007). However, spectroscopic observations point toward objects with few (if any) hydrogen still present in the envelope, leading to the hypothesis that the progenitor of IGRBs is a Wolf–Rayet type star (e.g., Chevalier & Li 1999).

Recently Gendre et al. (2013) proposed that GRB 111209A could not be explained by the explosion of a Wolf–Rayet star, and it has properties that are markedly different from those of other GRBs, pointing possibly toward a new kind of high energy source. These so-called ultra-long GRBs (hereafter ulGRBs) last more than $10^4$ s. In Gendre et al. (2013), as well as in Stratta et al. (2013), several hypotheses regarding the progenitor were tested. The conclusion was that extremely massive stars, such as blue or yellow supergiant stars, can explain the observations. This result was later confirmed for GRB 111209A by Levan et al. (2014), who added a new member to the class: GRB 101225A.

More recently, Margutti et al. (2014) also showed the emergence of a new class of soft ultra-long events.

On the other hand, Virgili et al. (2013) claimed that ulGRBs are rather the tail of the distribution of normal long GRBs and as a matter of consequence do not correspond to a new class of possible progenitors.

Zhang et al. (2014) tried to estimate the actual duration of the central engine activity by modeling the overall light curve in X-rays (0.3–10 keV) and using a theoretical model to propose a measure of the duration. They define the burst duration in X-rays as the observable time over which the internal dissipation mechanisms produced inside the jet dominate the afterglow emission. They claim that the effective burst durations range continuously between 0.1 and $10^4$ s instead of the usual $T_{90}$ parameter measured in gamma-rays (15–150 keV for Swift) that displays a strongly peaked histogram around 30 s. Their conclusion is that there is no evidence for a different origin for ulGRBs, which are the tail of the distribution of IGRBs, albeit “how to prolong a GRB central engine duration with a compact progenitor star is an open question” (Zhang et al. 2014, page 4).

Whether or not ulGRBs can be accounted for by the tail of the distribution of IGRBs, it is rather difficult to explain a long lasting event with a compact star, and extending IGRBs to very long durations does not solve the problem. It is therefore important to understand whether there are two players instead of one in the game. For example, Evans et al. (2014) have suggested that ulGRBs may form a distinct class of long GRBs not because of their central engine but because of their circumburst environment. By analyzing the ulGRB 130925A they formulate the hypothesis that ulGRBs reside in very low
density environments that make the ejecta decelerate at times much longer than if they were in a denser medium. On the other hand, Piro et al. (2014) use the properties of the central engine to explain both the duration and the properties of the emission. Only one explanation is valid, and it is related to the intrinsic nature of ulGRBs.

In this article we address the question on observational grounds, splitting the problem in two parts: are the overall properties of ulGRBs distinct from an observational point of view from those of normal long events, or are their properties compatible with the extension of the IGRB class toward very long durations? In any case, whether or not the progenitor of a ulGRB is different from IGRBs, a mechanism has to be found to explain them or eventually to unify them. Should ulGRBs belong to the IGRB class, a second question arises, that is, whether the collapse of a 10–15 solar mass Wolf–Rayet type star can explain ulGRBs. We answer this question in the second part of the paper.

We stress that the purpose of this paper is not to discuss the nature of individual bursts but rather the nature of a class of events.

In Section 2, we introduce a new measure for the burst duration in X-rays (0.3–10 keV), and we define ulGRBs using this measure. Then, in Section 3, we present our sample. In Section 4 we perform a statistical analysis to determine whether ulGRBs can be the tail of IGRBs. We discuss the results and the need for a new class of progenitors in Section 5 before concluding.

In the following, all errors are quoted at the 1σ level except when stated otherwise.

2. THE PARAMETER $T_X$

The ulGRBs are exceptional in terms of their burst duration in X-rays. More specifically, these GRBs have ultra-long emission duration up to the so-called “steep decay phase” in the observed X-ray light curve (Nousek et al. 2006). The origin of this emission is likely associated with the burst’s “prompt emission” for which internal dissipation mechanisms were invoked, where the steep decay phase has been interpreted to mark the end of the prompt phase (Kumar & Panaitescu 2000; Zhang et al. 2014).

In order to define ulGRBs, we fix, somewhat arbitrarily, the temporal boundary between long and ultra-long GRBs at 10$^3$ s. However, as shown in 4, fixing the boundary at a lower value, down to 1000 s, does not change the conclusions, as an excess is still present.

In this work we define an empirical parameter $T_X$ as the epoch at which the steep decay phase, monitored in X-rays (0.3–10 keV) just after the burst trigger, starts. This parameter can be considered as a proxy of the X-ray counterpart of the GRB burst duration typically estimated in gamma-rays (e.g., $T_{90}$). We do not consider here flares or late time steepening of the X-ray light curves, which have been suggested to be evidence of delayed central engine activity (e.g., Zhang et al. 2014), though no firm conclusions have yet been reached.

To quantify the rarity of ulGRBs, we compare the values of $T_X$ for all those long GRBs for which an estimate of this parameter was feasible from Swift/XRT monitoring.

We note that using X-ray data from Swift/XRT enables us to avoid two main biases that plague in general the GRB burst duration estimates and in particular the very long and ulGRB burst duration: (1) the spectral dependence of the burst duration; (2) the satellite orbit constraints that prevent a proper estimation of the duration of those GRBs longer than about 1000 s in the case of Swift.

Indeed, the fixed X-ray energy band for all the analyzed long GRBs ensures a spectrally homogeneous duration estimate. Moreover, Swift/XRT monitoring typically starts <100–300 s after the BAT burst trigger and its first continuous observation lasts for about 1000 s on average. Therefore, prompt emission phase analysis using Swift/XRT data is not biased against long GRBs with prompt emission lasting several hundreds of seconds. A recent analysis of the duration distribution of the time (scaled in the GRB rest frame) at which Swift’s first continuous observation of each GRB ends, for which no cut-off is observed, demonstrates that observational effects do not significantly bias bursts longer than >2000 s (Evans et al. 2014).

3. GRB SAMPLE

3.1. Building the Sample

To build the sample we use the Swift XRT GRB online catalog which contains Swift-XRT results for all Swift/GRBs. It provides the best-fit parameters for an automated light curve analysis (see details on the catalog in Evans et al. 2009). To model the overall shape of the light curves, multiple power law segments $f(t) = kt^{-\alpha}$ are assumed. Flare episodes are considered as extra components in the XRT GRB catalog analysis, and removed during the estimation of the power law parameters.

We prepared an automated method to extract the break time of the start of the steep decay from the abovementioned catalog. As can be seen in Figure 1, the temporal break of interest can be the first, the second, or sometimes the third occurring break. We set the following rules (indicated in order of priority):

1. a steep decay has $\alpha_i > 2.2$;
2. if $\alpha_1 > \alpha_2$ and $\alpha_1$ is steep, then the start time of the observation is larger than $T_X$;
3. if $\alpha_1 < \alpha_2$ and $\alpha_2$ is steep, then the first break time is $T_X$;
4. if $\alpha_1 < \alpha_2 < \alpha_3$ and $\alpha_3$ is steep, then the second break time is $T_X$;
5. if $\alpha_1 < \alpha_2 < \alpha_3 < \alpha_4$ and $\alpha_4$ is steep, then the third break time is $T_X$;
6. et cetera.

The application of rule 2 leads to upper limits for $T_X$. In the following we consider the start epoch of the Swift/XRT monitoring, $T_{\text{start}}$, as a $T_X$ proxy (i.e., in the case of rule 2 $T_X = T_{\text{start}}$). In order not to bias our sample we removed all bursts with a follow-up delay by more than 500 s after the trigger time.

The value of the critical decay index, 2.2, is given by the electron energy distribution ($p$) of the fireball. In the standard fireball model, all segments of the light curves during the afterglow part are supposed to have a decay index lower than or equal to $p$. Using $p > \alpha$ thus removes all normal cases of the fireball afterglow emission, leaving only the steep decay phase and possibly some sections post-jet break. We consider this last case by stopping at the first applicable rule, from the above ordered list (this prevents interpreting late jet breaks as the end of the prompt phase).

The final sample for which we could provide a secure $T_X$ estimate counts 207 GRBs from an original sample of 243 GRBs taken from the catalog. They are listed in Table 1.

3 http://www.swift.ac.uk/xrt_live_cat/
We conservatively excluded all these bursts from our sample. Assessing whether any earlier steep decay phase was present. Between the BAT and the XRT monitoring, preventing us from finally, GRB 061019 presents an unusually large temporal gap and resembled more a small flux dip in the light curve. Two other cases (GRB 110422A with epoch afterglow steepening not filtered out by our method. In 111229A, GRB 090929B, and GRB 081029, this is due to a late presence of an early steep decay phase at a few 10–100 s of the steep decay start epoch, as explained below. Δ characterizes by a very short duration with for GRB 060813, GRB 111229A, and GRB 090929B and a few 100–1000 s for GRB 081029 after the trigger. For GRB 111229A, GRB 090929B, and GRB 081029, this is due to a late epoch afterglow steepening not filtered out by our method. In two other cases (GRB 110422A with TX = 1.2 ks and 080721A with TX = 24.5 ks), the individual steep decay phase was characterized by a very short duration with ΔT/T < 0.05–0.2 and resembled more a small flux dip in the light curve. Finally, GRB 061019 presents an unusually large temporal gap between the BAT and the XRT monitoring, preventing us from assessing whether any earlier steep decay phase was present. We conservatively excluded all these bursts from our sample.

We now turn to the specific case of GRB 130925A (Evans et al. 2014; Piro et al. 2014) which has a claimed duration of more than 20 ks. According to our classification this burst has TX = 149 s, which does not make it remarkable. This could be a consequence of its very strong flaring activity, which was used to claim its ultra-long origin. In addition, the BAT trigger for this burst occurred 160 s after the start of the INTEGRAL observations. Therefore, the prompt duration in X-rays is underestimated. Even if we take into account this delay, the resulting duration does not classify GRB 130925A as a ulGRB. Nevertheless, given the interest in this GRB and its properties, we test its addition to the sample in our analysis (see 4).

### 4. X-RAY PROMPT DURATION DISTRIBUTION

Our final sample is characterized by a mean TX = 337 s and a median of 119 s, for a range of values that goes from a minimum of 49 s up to 25,400 s. These values confirm that the X-ray burst counterpart up to the start of the steep decay phase lasts about one order of magnitude longer than the hard X-rays or gamma-ray emission duration (Tk). This result is similar to the results reported by Zhang et al. (2014), although we use a different temporal parameter.

Let us examine the question of the tail of the burst duration distribution being able to account for a few ulGRBs: for this purpose, we fit the distribution of TX with both a log-normal and a generalized extreme value (GEV) probability distribution function, using the Matlab software package for data analysis. We use GEV because it fits distributions with an extended tail better, therefore giving a more stringent constraint on the rejection of the hypothesis that ulGRBs’ TX belongs to the “regular” distribution of lGRB durations. The distribution of the logarithm of TX is plotted in Figure 2, together with the fits for the log-normal distribution applied to the whole sample and to the log-normal distribution applied to the sample excluding durations larger than 300 s, and the GEV applied to the whole sample. Our T5 sample has 26/207 bursts (12%) with T5 > 300 s, 7 bursts (3.3%) with T5 > 630 s, 5 bursts (2.4%) with T5 > 1000 s, and 1 (0.5%) with TX > 10 ks.

A log-normal model, applied to the whole sample, does not provide an acceptable fit of the distribution. By performing a one-sample KS test we obtain a value D = 0.17, corresponding to a null hypothesis probability of 2 × 10−5. Selection effects

### Table 1

| GRB           | TX (s) |
|---------------|--------|
| GRB 13069B    | 453    |
| GRB 130427A   | 140    |
| GRB 130315A   | 160    |
| GRB 120324A   | 76     |
| GRB 120213A   | 166    |
| GRB 111123A   | 647    |
| GRB 111121A   | 111    |
| GRB 110420A   | 87     |
| GRB 110119A   | 82     |
| GRB 100814A   | 261    |
| ...           | ...    |

(This table is available in its entirety in machine-readable form.)

### 3.2. Peculiar Events Removed from the Sample

We visually inspect the BAT plus XRT light curve of our sample of GRBs. We find that on average for TX < 500 s the estimate of the start epoch of the steep decay phase is accurate enough for our purposes (e.g., within 5%–10%).

For GRBs with TX > 500 s we found some mis-identifications of the steep decay start epoch, as explained below.

The comparison between the BAT and XRT fluxes suggests the presence of an early steep decay phase at a few 10–100 s for GRB 060813, GRB 111229A, and GRB 090929B and a few 100–1000 s for GRB 081029 after the trigger. For GRB 111229A, GRB 090929B, and GRB 081029, this is due to a late epoch afterglow steepening not filtered out by our method. In two other cases (GRB 110422A with TX = 1.2 ks and 080721A with TX = 24.5 ks), the individuated steep decay phase was characterized by a very short duration with ΔT/T < 0.05–0.2 and resembled more a small flux dip in the light curve. Finally, GRB 061019 presents an unusually large temporal gap between the BAT and the XRT monitoring, preventing us from assessing whether any earlier steep decay phase was present. We conservatively excluded all these bursts from our sample.

![Template light curve with the notation used in this article. We present two examples. Left: one single break. Our method allows us to discriminate whether this break is prompt related or jet related. Right: a complex three-break light curve. In this example, the start of the steep decay is the second segment (α2 > 2.2), and rule 3 (applied before rule 4) prevents the association of the start of the steep decay with the third segment.](image-url)

![Flux (arbitrary unit) vs. Time (arbitrary unit) for GRBs in our sample.](image-url)
might play a significant role in this result: for example, the small-duration left tail of the distribution is likely biased against short duration long GRBs since the Swift/XRT monitoring typically starts few 10–100 s after the trigger (Figure 1). However, even when removing events shorter than 300 s from the sample and using a truncated log-normal model (with the mean and standard deviation of the log \( T_x \) sample) we still do not obtain an acceptable fit.

Interestingly, it is by excluding the long duration tail up to \( T_x > 300 \) s that we could nicely fit the distribution. For example, keeping only events for which \( T_x < 300 \) s, we get \( \chi^2 = 13 \) for 15 dof (while for \( T_x < 2000 \) s we get \( \chi^2 = 150 \) for 14 dof). This could indicate that our limit for ulGRBs (\( 10^4 \) s) is too conservative, and a value of \( T_x > 10^3 \) s should be more representative of this new class.

The GEV distribution provides a better fit than the log-normal, though it is not ideal because of the presence of a (small) excess of \( T_x \) around 400–500 s. The parameters are \( \mu = 1.99 \pm 0.02 \) (the location, i.e., 97.7 s), the scale \( \sigma = 0.19 \pm 0.01 \), and the form factor \( \xi = 0.17 \pm 0.05 \). Using this probability we get a prediction of 21 events above 400 s, although 19 are observed. However, the same law gives the probability of getting a point above \( 10^4 \) s to be \( 2 \times 10^{-3} \).

We tested the addition of GRB 130925A by adding its claimed duration of 20 ks (Pirol et al. 2014) and obtained a very similar result. These results clearly indicate the presence of an excess of detected ulGRBs with respect to the two distributions tested. Though this excess is already noticeable above 1 ks, the presence of a GRB above 10 ks is clearly an outlier.

We note also that Virgili et al. (2013) have used the \( t_{90} \) duration from Swift/BAT measurements (15–150 keV) while very long and ultra-long GRBs are characterized in the X-ray band (0.3–10 keV). In addition they computed the burst duration using either the BAT or the XRT data, making the sample inconsistent as the duration evolves strongly with the energy.

On the other hand Zhang et al. (2014) propose a new measure of the burst duration in X-rays based on the time during which X-ray flares, taken as a proxy for the duration of the emission of the internal engine, are still emitted. Using this method, they derive a distribution of burst duration that continuously spans the interval from 0.1 to \( 10^6 \) s. Doing so, the duration of normal long GRBs is extended. However, this burst duration measure is based on the interpretation that internal shocks are emitted continuously during the event.

This argument should be taken with caution. Nousek et al. (2006) have studied the generic X-ray light curve of the afterglow using Swift data. They find that the prompt event is rapidly followed by a steep decay, a break into a shallow decay phase, and a second break into a “normal” decay phase, with possible flares superimposed on both phases. The current interpretation of the phase after the steep decay is the start of the afterglow (e.g., Willingale et al. 2007). From that point, the central engine is not supposed to inject a significant amount of energy into the fireball, and most (if not all) of the accretion (that fuels the central engine) should have been completed. Indeed it is on these considerations that we have based our burst duration definition.

It is true that late flares are sometimes observed in the light curves of IGRBs. However, the interpretation of X-ray flares as indications of central engine activity is still under debate (Lazzati et al. 2011; Swenson & Roming 2014). Flares can be due to renewed or continuing activity of the central engine. They could also be due to a refreshed internal shock due to the (possible) slow velocity of the last blobs of matter ejected by the central engine. Consequently, the time of the last X-ray flare could measure the velocity of the slowest shells rather than the duration of the central engine activity. While the latter case would validate Zhang et al.’s (2014) proposed definition, the former would make it more ambiguous as it would imply a latency time still accounted for by the measure of the burst duration, even if the central engine is not active.

5. DISCUSSION

5.1. The Burst Duration Issue

Other authors, for instance Virgili et al. (2013), have proposed that a duration of a few thousands of seconds was consistent with the fit of the duration distribution so far. This is quite understandable, as the fitting procedure is not a statistical test but a way to approximate an actual distribution with a (given) functional. However, we show that the probability that they belong, as a population of several events, to the same distribution is rejected to a high level of confidence.
We thus conclude that ulGRBs cannot be accounted for by the tail of the duration distribution of the long GRBs, and that there is a statistical difference in these two populations.

5.2. Should the Progenitor be Different?

In Section 4 we demonstrated that IGRBs and ulGRBs are different with a large probability. Several mechanisms could explain this difference (Evans et al. 2014; Gendre et al. 2013). The question is whether the progenitors of ulGRBs are the same as the progenitors of normal long GRBs. The duration alone will not give the answer: as a parallel case, a binary progenitor (Eichler et al. 1989) and a magnetar progenitor (Usov 1992) have both been proposed for short GRBs; both produce the same event duration. This argument has also been pointed out by Zhang et al. (2014), indicating that more studies are needed before claiming a progenitor.

The analysis we have performed here on the duration distribution showing that ulGRBs are not an extended tail of IGRBs is not the only piece of evidence that suggests two distinct classes of events. GRB 111209A and GRB 101225A also have several specific properties that differentiate them from other IGRBs (see details in Thöne et al. 2011 for GRB 101225A; Gendre et al. 2013, Stratta et al. 2013 for GRB 111209A; Piro et al. 2014 for GRB 130925A). For instance, the spectral properties of GRB 111209A as well as GRB 101225A present some differences from the rest of the IGRBs: there is a detectable thermal emission during the prompt phase of these bursts. Normal long GRBs do not present a thermal emission, but rather the well-known non-thermal “Band” law (Band et al. 1993). Combining the unusual duration with their peculiar properties and different spectra, we can conclude that GRBs 111209A and 101225A are notably different from classical IGRBs, in line with recent results obtained by Margutti et al. (2014). A similar analysis has been made for sGRBs, and a GRB is considered as a member of the sGRB “class” if it is both “short” and “hard” (see, however, Siellez et al. 2014, for a detailed analysis of sGRBs in the rest frame).

Gendre et al. (2013), following Woosley & Heger (2013), proposed a different kind of progenitor because of the difference in the duration of the central engine.

Another obvious point is then how long bursts are produced without flares that last a few tens of seconds: the usual Wolf–Rayet progenitor would then have problems accounting for “short long events.”

An additional indication for late time activity is the second steep decay phase which has been observed in a few GRBs and whose origin remains unclear; given that there is no obvious explanation for this, we could not take these relatively rare features into account.

In reality, one of the problems in interpreting the duration of GRB 111209A is the fall back time of the external layers on the central black hole. In the case of ulGRBs we do see a continuous emission of the burst source for more than 6000 s in gamma-rays, and 20,000 s in X-rays, both emissions being strongly correlated during the time when they were observed together. Though it is probably not the only possibility, accretion from a very extended source like a supergiant star is a natural hypothesis as proposed already by Woosley & Heger (2013).

We note that an identical debate on GRB classification arose with GRB 790305b, the so-called “5th March event.” When discovered, this event could have been taken to be compatible with the origin of other GRBs (thought at that time to originate from thermonuclear explosion on galactic neutron stars), or as the single known member of another class of events (Barat et al. 1979; Mazets et al. 1979). The issue was settled with the discovery, eight years later, in 1987, of the multiple recurrences of GRB 790107, better known now as the magnetar SGR 1806-20 (Atteia et al. 1987; Laros et al. 1987). It is not the first time that the GRB community hesitates to recognize the specific origin of “peculiar” events: the reason for the doubts is that when applied to small samples, statistical tests cannot discriminate between a large sample of GRBs and the few events claimed to belong to the new “class.” Physics has to be applied to check whether or not it is possible to use the same model for the “peculiar” events.

The case with ulGRBs is the same. Two events have a duration one order of magnitude longer than the longest IGRBs and their spectral properties during the prompt phase are markedly different from other “classical” long GRBs. Together, these two pieces of evidence lead us to consider these events to be at the very least “peculiar” and difficult to explain within the framework of the classical Wolf–Rayet hypothesis for their origin. It is of course possible that this hypothesis still applies, but a mechanism has to be proposed to explain that extended duration. By extending the duration of all IGRBs, as proposed in Zhang et al. (2014), an acceptable explanation should be found for a large part of the IGRB class.

6. CONCLUSIONS

In this paper we showed that the properties of several bursts, such as GRB 111209A, are outstandingly different from that of other IGRBs, making them representative of a new category of bursts, the ulGRBs. Does another progenitor type better explain the observations? In Gendre et al. (2013) and Stratta et al. (2013) we proposed several possible progenitors, which all imply a larger reservoir feeding the prompt event. Any model of the origin of ulGRBs should account for a large available mass, distributed in such a way to reproduce the extreme duration of the events. Moreover, we already noted in Gendre et al. (2013) that the properties of these bursts make their detection very difficult, if not impossible, at redshifts larger than one. Such models should then take into account the properties of the “local” universe, when compared to very distant events.

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Facility: Swift

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