Identification of GRB precursors in Fermi-GBM bursts

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(Dated: April 8, 2020)

We present an analysis of more than 11 years of Fermi-GBM data in which 217 Gamma-Ray Bursts (GRBs) are found for which their main burst is preceded by a precursor flash. We find that short GRBs (<2 s) are ∼10 times less likely to produce a precursor than long GRBs. The quiescent time profile is well described by a double Gaussian distribution, indicating that the observed precursors have two distinct physical progenitors. The light curves of the identified precursor GRBs are publicly available in an online catalog (https://icecube.wisc.edu/~grbweb_public/Precursors.html).

Introduction — Gamma-ray bursts (GRBs) are cataclysmic transient cosmic events characterized by the emission of one or multiple flashes of gamma radiation. They are the most powerful outbursts of electromagnetic radiation in our universe and a possible source of (ultra) high-energy cosmic rays [1, 2]. The duration of GRBs can be described using a bi-modal distribution indicating the existence of two progenitor source classes. In general, bursts lasting longer than 2 s are related to the collapse of a super-massive star, as confirmed by the observation of type-Ic supernovae in coincidence with long GRBs [2, 3]. Short bursts, lasting less than 2 s, are believed to occur when two co-orbiting neutron stars collide. Evidence for this model was recently obtained by the detection of gravitational waves from a binary neutron star merger followed by a short GRB [4, 5].

The main outburst of gamma radiation, called the prompt phase, is followed by an afterglow stage in which the ejected matter collides with the surrounding medium. Thanks to multi-wavelength observations, ranging from X-ray to radio, the physical processes related to this afterglow emission are well understood. Apart from the prompt and afterglow phases, there is a third emission phase, called the GRB precursor. Precursors are typically defined as relatively dim gamma-ray flashes that occur before the prompt emission. Previous studies [6–10], comprising GRBs up to the year 2014, found that precursor flashes occur in a subset of both long and short GRBs. The fraction of bursts in which a precursor is observed strongly depends on the method and criteria used to define a precursor and typically ranges from 3% to 20%.

Numerous models have been proposed to explain precursor flashes in both long and short GRBs. These include photospheric emission [17, 19], pre-burst jets, [20, 21] and interactions between magnetized neutron stars [22, 23]. Currently, there is no consensus on the origin of precursor flashes and, most likely, more than one model will be needed to explain all observed precursors. Given that precursors only occur in a subset of all GRBs, an extensive study is thus required to uncover the physical origin of GRB precursors.

We performed an automated search that identifies precursor flashes observed by the Fermi-GBM detector [24]. Out of a total sample of 2364 GRBs, 244 precursors were identified originating from 217 GRBs, of which 158 are newly identified GRBs with precursor emission.

In this letter, we present the details of our selection and show that short GRBs are ∼10 times less likely to produce a precursor than long GRBs. We performed an analysis on the quiescent time profile, given by the times between the precursor flash and the main burst. The increased statistics from our search allowed us to identify a novel feature in the quiescent time profile, which is well described by a double Gaussian distribution, indicating that the observed precursors have two distinct physical progenitors. To allow for follow-up studies, searching for coincidences with other astrophysical messengers, such as neutrinos and gravitational waves, the obtained results of our analysis are presented in the supplemental material and have been made available via an online tool [25].

Data — The Fermi Gamma-ray Space Telescope is currently the most efficient GRB detection satellite in orbit. Its two main instruments are the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM). Whereas LAT has a sky coverage of 20%, GBM continuously observes the full region of the sky not occulted by Earth. On average, the GBM and LAT detect 240 and 18 GRBs per year, respectively [26, 28]. In this study we analyzed 2684 GRBs, using all GBM recorded bursts up to the year 2020.

The GBM telescope is composed of 12 sodium iodide (NaI) and two bismuth germanate (BGO) detectors. Trigger and localization information is provided by the NaI detectors, which are sensitive to gamma-rays of 8 keV to 1 MeV. The BGO detectors, which will not be used in this analysis, are sensitive from 200 keV to 40 MeV and serve to cover the energy gap with the LAT [27].

The GBM burst data was obtained from the Fermi Science Support Center [24] and provides the raw photon counts as a function of time and energy for each of the 14 detectors. Time-Tagged Event (TTE) data provides the highest temporal resolution of 2 µs. Since August 2010, TTE data is available over a time window [t_\text{tr}−135 s, t_\text{tr}+300 s], where t_\text{tr} is the GBM detector
trigger time. Before August 2010, TTE data is only available starting 30 s before \( t_{tr} \), but again up to 300 s after \( t_{tr} \). CTIME data is provided over a 2000 s time window centered around \( t_{tr} \), but has a coarser nominal resolution of 0.256 s. To allow the detection of very short emission periods, we have used TTE data whenever available. CTIME data was used to extend the examined time window to 1000 s before and after the trigger time.

During normal operation, the Fermi telescope functions in a sky survey mode [29]. To allow full sky monitoring of the LAT telescope, the orientation of the detector continuously changes. As such, the background rates of the GBM detectors vary with time. A linear background rate approximation can however still be used over periods of time less than 100 s, as the period of the oscillatory motion of the spacecraft is on the order of 3 hours [27, 29].

**Method**— For every burst, we select the GBM NaI detectors that were triggered by the GRB. If more than three detectors were triggered, only the three triggered detectors which were pointing closest to the burst location are used. The data analysis is two-fold. An initial analysis on raw time data is performed to characterize the background, allowing to capture global fluctuations. Subsequently, a Bayesian Block (BB) algorithm [30] is used to select the physical signal regions.

Our analysis aims at identifying all emission periods in which gamma-ray activity is observed from the detected GRBs. This is achieved by constructing background subtracted light curves. For more than 90% of the identified bursts, a stable background fit is first obtained between 800 s and 1000 s before \( t_{tr} \), marking the start time of the analysis interval. The end time of the analysis interval is set 50 s past the end of the Fermi T90 interval, defined as the central time window that contains 90% of the fluence of the GRB. For bursts whose T90 exceeds 250 s, this end time is extended to 20% of the T90 time beyond the T90 interval. One final consideration is that a minority of all bursts have one or more gaps in their light curves due to missing data. For those bursts, we only examine the continuous data taking period containing \( t_{tr} \). This choice is motivated by the observation that for less than 1% of all bursts, additional data is available at earlier times.

We automated the selection of background time intervals in which no increased gamma-ray activity is observed. Our selection is therefore fully reproducible and based on physically motivated parameters. Background times are selected based on the requirement that the rate does not undergo a sudden increase. For this purpose, we use an algorithm similar to the Fermi-GBM online trigger [27], which compares the observed rate to a prediction based on a fit to the rate at earlier times. The rate in the identified background intervals is then extrapolated to intermediate, possible signal, regions. As such, we obtain an estimate for the background rate over the full light curve. A more detailed description of this method is provided in the supplemental material.

Having characterized the background rate, we proceed by rebinning the data using the Bayesian Block (BB) algorithm [30]. The BB algorithm was specifically designed to identify localized structures, such as bursts, in GRB light curves. It optimizes both the number of bins and the location of the bin edges by maximizing a fitness function. For every selected GBM detector, we construct a BB light curve. In addition, a single BB light curve based on a combination of the photon counts of the selected detectors is also constructed for every burst. These combined light curves contain the largest statistics and will thus serve as the basis for our selection. To illustrate the BB procedure, the light curve of GRB 190114C is displayed in Fig. 1.

**Analysis**— To quantify the physical signal, a background subtraction procedure is applied. The background rate is integrated over each bin to estimate the
FIG. 2. Relative number of GRBs that are not detected within 5 s of the trigger time $t_{tr}$ (full orange line) as a function of the threshold rate $r_{th}$. The same relation is shown for bursts that are detected more than 500 s before the trigger time (blue dashed line), where few to no precursors are expected [10]. The shaded grey bands show the 1σ statistical uncertainty for both curves. In our analysis, the threshold rate is set equal to 30 Hz, indicated by the vertical line.

The threshold rate $r_{th}$ is based on the trade-off of minimizing the number of false positives, whilst maximizing the sensitivity of the search. Ideally, every event triggering the GBM detector should also be selected by our analysis. To estimate the loss of sensitivity as a function of $r_{th}$, we therefore consider the fraction of GRBs in which, following our selection criteria, no excess is observed within 5 s of the GBM trigger time $t_{tr}$. This quantity is shown as the full orange line in Fig. 2 and shows a slow but steady increase as a function of $r_{th}$.

To estimate the false positive rate, we consider the number of GRBs which, following our criteria, yielded an emission episode which could be identified as a precursor in the period from 1000 s to 500 s before the Fermi-GBM trigger time $t_{tr}$. This time window is based on a previous study presented in [10], which, using a sample of 956 Fermi-GBM observed bursts, found only a single burst in which a precursor event occurred more than 500 s before $t_{tr}$. For our analysis, the fraction of GRBs which yielded a signal in this time range is displayed by the dashed blue line in Fig. 2 as a function of the threshold rate $r_{th}$. A plateau is reached at $r_{th} > 30$ Hz. We therefore set $r_{th} = 30$ Hz, as this corresponds to the minimal value for which the estimated false positive rate approaches the plateau at $\sim 0.5\%$, leading to an expected false positive rate $r_f$ of $1.7 \times 10^{-5}$ Hz. Considering that, on rare occasions, precursors do occur more than 500 s before the prompt emission [31], this approach is expected to result in a conservative estimate of the true false positive rate.

We define an emission episode as a continuous period of increased emission in the background subtracted light curve. If a GRB has two or more emission episodes, we verify that the intermediate quiescent periods contain enough statistics to ensure that the rate has dropped back to the background level. Quiescent periods for which the Poisson uncertainty on the average background rate exceeds 5% are disregarded. For a typical burst [32], this corresponds to a lower limit on the allowed duration of the quiescent period of $\sim 0.2$ s.

Having obtained our signal regions, we define the prompt signal phase as the emission episode with the largest fluence. If one or more emission episodes precede the prompt phase, we select them as GRB precursors. As a final check in our selection procedure, the light curves of all GRBs for which precursor emission is found are inspected by eye. This allows to verify that the identified emission was based on a reliable fit to the background rate and that the GBM detector was in a stable operation mode at the time of the GRB.

**Results**—Applying our signal selection method on all 2684 bursts, we find 320 GRBs that were triggered by Fermi-GBM, but do not show a signal following our criteria. In the following, we therefore restrict ourselves to the 2364 bursts for which a signal is found.

Our analysis identified 244 precursor emission episodes spread over 217 GRBs. We thus find that 9% of all GRBs have one or more precursors. Any given burst is observed to have at most 3 precursors. The number of bursts having 1, 2 and 3 precursors corresponds to 192, 23 and 2, respectively. Considering the combined time preceding the prompt emission of all GRBs, equal to $2.1 \cdot 10^6$ s, the expected number of false positives in our analysis is 36.1±8.8 (stat. only), roughly 15% of the full sample.

A complete catalog containing the start time, the duration, and the time separation of the precursors with respect to the prompt phase is given in the supplemental material or can be accessed via the online tool [25].

To interpret the observed fraction of GRBs with precursors, one should consider that our analysis will be unable to identify precursor emission if the burst is too faint. Alternatively, if the prompt emission of a faint burst has multiple peaks, the first peak(s) might be erroneously identified as precursors. However, in 80% of all precursors, the time interval between the start of the precursor and prompt emission exceeds 10 s, making it less likely that the identified precursor is actually part of the prompt phase.

A subdivision can be made based on the duration of the bursts. While 14% of the 2364 examined bursts are short GRBs, only four (1.8%) of the 217 bursts with precursors are short GRBs [33]. For each of these 4 bursts, we observe that the precursors occur within 2 s before
the prompt emission. All 4 short GRBs have a precursor that is shorter in duration than the prompt phase and their quiescent times are consistent with one another up to a factor \( \sim 3 \). While limited in statistics, we note that the time intervals between the onset of the precursor and prompt emission are smaller than the 1.7 s time gap separating the gravitational waves and the gamma-rays that were observed from GRB 170817A [5].

Fig. 3 displays the full distribution of the quiescent time between a precursor and its subsequent emission episode. Two populations are observed, crossing over at \( \Delta t_Q \sim 2 \) s. Applying a two component Gaussian fit, we obtain a reduced \( \chi^2 \)-value of 1.23 assuming Poisson errors on the number of events. The two Gaussian distributions peak at 0.57 s and 27 s and have a weight of 12% and 88%, respectively. Performing a single component Gaussian fit, thus simplifying our model by neglecting the excess at \( \Delta t_Q \lesssim 2 \) s, we observe that the reduced \( \chi^2 \)-value increases to 8.87.

The leftmost component of the double Gaussian fit in Fig. 3 could have several origins. A first contribution is found from the precursors of short GRBs, though they can only account for \( \sim 15\% \) of the observed excess. A second contribution could come from bursts whose observed flux drops below the observable limit in between different peaks of the prompt phase, falsely identifying a precursor emission during the prompt phase. Figure 3 illustrates that bursts with \( \Delta t_Q < 2 \) s are on average less bright than bursts with longer quiescent periods. This does not, however, hold for all bursts. A case in point is GRB 190114C, shown in Fig. 1, whose second precursor ends 1.32 s before the start of the prompt emission. We thus observe that a subclass of long GRBs do have physical precursors occurring within two seconds of the prompt emission. Given the short time scale, this could indicate that the precursors of those bursts originate from a different physical mechanism.

A related study of quiescent times was performed in [10], where a strong linear correlation between the duration of the quiescent time \( \Delta t_Q \) and that of the subsequent emission episode \( \Delta t_{sub} \) was found. However, due to lack of data, redshift effects, which could naturally induce such a linear correlation, were not considered. To probe possible redshift effects, we determined the correlation between \( \Delta t_Q \) and \( \Delta t_{sub} \) for the 21 bursts in our selection with known redshift \( z \), and apply a correction for redshift. The obtained Pearson correlation factor is 34%. To determine the significance of this value, we composed a test statistic distribution by calculating the correlation coefficient between random combinations of the quiescent times and secondary emission episodes. Based on this distribution, we obtain a \( p \)-value of 7.1%. No significant linear correlation is thus observed between the duration of the quiescent time following precursor episodes \( \Delta t_Q \) and the duration of the secondary emission episode \( \Delta t_{sub} \).

Quiescent times also provide an independent probe to investigate potential differences between the precursor and prompt emission. Previous studies generally found that precursor emission exhibits the same spectral properties and evolution as prompt emission [6, 7, 9, 11, 14, 34]. In the case of long GRBs, this observation can be embedded in a model in which the precursor and prompt emission correspond to different shells of matter falling onto the central engine [2, 12, 13]. A parameter that could be sensitive to this hypothesis is the quiescent time in between emission episodes. Figure 4 shows the distribution of the quiescent time between two precursors (red) and between precursor and prompt emission (blue). To quantify their resemblance, we test if the two data sets were drawn from the same parent distribu-
tion using a two-sample Kolmogorov-Smirnov test. The maximal separation between the cumulative distributions is 28.7%, resulting in a p-value of 3.0%.

One object in our selection is of special interest, GRB 190114C, a particularly bright burst that occurred on the 14th of January 2019 [35]. GRB 190114C/BN190114873 is the first GRB from which TeV photons have been detected, as observed by the MAGIC telescope in La Palma [30]. Our analysis identified two faint precursors occurring 5.57 s and 2.85 s before the start of the prompt emission and lasting 1.94 s and 1.54 s, respectively. The detailed light curve of this burst is shown in Fig. 1.

Conclusion—By applying a fully automated precursor search on the light curves of 2364 GRBs, we identified a total of 244 precursors spread over 217 bursts. Only four of those precursors occurred for short GRBs. We thus find that the fraction of long and short GRBs with one or more precursors equals 10.5% and 1.2%, respectively. All precursors for short GRBs occurred within 2 s before the start of the prompt emission. A notable long GRB for which we found two precursors is the extremely bright GRB 190114C. This burst was preceded by two dim precursors, indicating that gamma-ray production was already ongoing 5.6 s before the start of the prompt emission.

Apart from studying individual bursts, we also examined the quiescent time of all GRB precursors. A bi-modal distribution is observed, possibly indicating that precursors can have two types of progenitors. In addition, no clear correlation is found between the quiescent time and the duration of the subsequent emission episode. Follow-up studies to further examine these claims are encouraged. To this end, and to allow other multi-messenger correlation studies, we have included a full list detailing the emission times of the identified precursors in the supplemental material and the online tool [25].

We are grateful for the public data made available by the Fermi-GBM collaboration. In addition, we would like to explicitly thank S. Zhu for providing a reference precursor catalog, and the IceCube collaboration for hosting our online database. This work was supported by the Flemish Foundation for Scientific Research (FWO-G007519N) and the European Research Council under the European Unions Horizon 2020 research and innovation program (No 805486 - K. D. de Vries).
SUPPLEMENTARY MATERIAL

Background characterization—During normal operation, the Fermi telescope functions in a sky survey mode [29]. This implies that the orientation of the spacecraft continuously changes to allow the LAT telescope to monitor the entire sky. A downside to this mode of operation is that the background rates of the GBM detectors are changing with time. A linear approximation can still be used over periods of time less than 100 s, as the period of the oscillatory motion of the spacecraft is on the order of 3 hours [27,29].

During previous searches, the time ranges used to estimate the background rate were generally set by hand [7–9]. Since we plan to examine a time range of 2000 s for over 2000 bursts, this would become a very demanding endeavor. Therefore, we automated the selection of time intervals in which no increased gamma-ray activity is observed. This method has the added advantage that the selection is fully reproducible and based on physically motivated parameters.

The tagging of background time intervals is illustrated in Fig. 6 and based on the assumption that the observed rate can be predicted using the rate at earlier times. To predict the background rate at an arbitrary time \( t \), we perform a linear fit to the data in the time interval \([t_1 - 30\ s, t_1 - 10\ s]\). By extrapolating the fit to time \( t \), we obtain a prediction \( r_p \) for the background rate at time \( t \). This prediction is then compared to the true rate \( r_t \) found at time \( t_1 \), averaged over 2.5 s. As long as the true rate is within a 3\( \sigma \) Poisson upper-fluctuation of the predicted background rate, i.e.

\[
r_t < r_p + 3 \cdot \sqrt{\frac{r_p}{2.5\ s}},
\]

the time \( t_1 \) is tagged as background. The next point in time \( t_2 = (t_1 + 1\ s) \) is then subjected to the same procedure, until a time \( t_n \) is found for which Eq. (1) no longer holds. To determine the length of the possible region of interest, we then proceed by verifying if the RMS of \( r_p - r_t \), averaged over a 10 s period centered around \( t_n + 25\ s \) is within 1.5\( \sigma \) of the Poisson expectation. By immediately advancing 25 s, we aim to overshoot the period with excess emission while still ensuring that the background can be well approximated by a linear extrapolation. If the RMS exceeds 1.5\( \sigma \), the rate is labeled as non-background and added to the analysis region. If, on the other hand, the RMS is sufficiently low, a new background interval is started at \( t_n + 25\ s \).

Using the approach outlined above, background regions are identified in each of the light curves. The background rate is then set equal to the true rate, averaged...
over 2.5 s, in these background intervals. In intermediate regions of interest containing possible signal, a linear interpolation is used based on the last and first point of the adjacent background intervals. Figure 6 displays a visualization of this procedure for GRB trigger bn150422703 and the GBM detector labeled nb.

Precursor catalog—To enable follow up studies, we provide a complete list of the emission times of all precursors identified by our analysis. Our catalog provides the start time of the prompt emission in UTC, the start time of the precursor emission with respect to the onset of the prompt emission, and the duration of the precursor emission. An electronic version of this table can be downloaded from [https://icetube.wisc.edu/~grbweb_public/Precursors.html](https://icetube.wisc.edu/~grbweb_public/Precursors.html).
Table I: Temporal properties of the identified precursors. For every GRB, we provide the start time of the prompt emission \( t_{\text{prompt}} \), the start time of the precursor emission with respect to \( t_{\text{prompt}} \) and the duration of the precursor emission. To access this table in a digital format, please visit [https://icecube.wisc.edu/~grbweb_public/Precursors.html](https://icecube.wisc.edu/~grbweb_public/Precursors.html).

| GRB          | \( t_{\text{prompt}} \) (UTC) | \( t_{\text{precursor}} \) (s) | Duration (s) |
|--------------|-------------------------------|---------------------------------|--------------|
| bn08023557   | 23:50:44.177                  | -11.612                         | 1.032        |
| bn080816503  | 12:04:39.495                  | -21.823                         | 5.596        |
| bn0808181579 | 13:54:44.895                  | -20.361                         | 4.320        |
| bn08032068   | 08:50:22.699                  | -8.559                          | 5.112        |
| bn081003644  | 15:27:27.738                  | -11.363                         | 4.320        |
| bn081121858  | 20:35:31.671                  | -8.498                          | 7.855        |
| bn090101758  | 18:13:07.574                  | -86.950                         | 6.082        |
| bn090113778  | 18:40:38.870                  | -0.475                          | 0.150        |
| bn090117335  | 08:02:26.183                  | -24.653                         | 1.296        |
| bn090131090  | 02:09:43.196                  | -22.324                         | 12.445       |
| bn090309767  | 18:25:41.699                  | -36.134                         | 6.122        |
| bn090326633  | 15:10:16.566                  | -583.057                        | 0.256        |
| bn090419997  | 23:55:38.751                  | -37.348                         | 23.251       |
| bn090425377  | 09:04:14.740                  | -44.805                         | 2.705        |
| bn090502777  | 18:40:11.917                  | -37.539                         | 3.065        |
| bn090510016  | 00:23:00.368                  | -0.420                          | 0.024        |
| bn090602564  | 13:32:22.296                  | -1.242                          | 0.683        |
| bn090610723  | 17:22:58.385                  | -90.937                         | 6.868        |
| bn090618353  | 08:29:16.651                  | -50.628                         | 28.946       |
| bn090702010  | 17:02:57.665                  | -0.776                          | 0.264        |
| bn090810659  | 15:50:40.542                  | -94.504                         | 43.262       |
| bn090816196  | 16:41:54.351                  | -4.958                          | 1.583        |
| bn090819560  | 22:48:30.233                  | -43.778                         | 18.577       |
| bn090819560  | 22:44:41.956                  | -179.466                        | 12.722       |
| bn090909095  | 12:13:25.368                  | -8.951                          | 4.124        |
| bn090907017  | 00:24:10.767                  | -1.967                          | 1.664        |
| bn090929190  | 04:33:04.488                  | -0.571                          | 0.122        |
| bn091108905  | 21:28:49.421                  | -9.606                          | 2.788        |
| bn100116897  | 21:32:19.006                  | -83.382                         | 6.319        |
| bn100307297  | 17:30:19.867                  | -65.378                         | 23.215       |
| bn100405566  | 13:34:36.243                  | -16.948                         | 15.677       |
| bn100323452  | 13:01:32.005                  | -54.935                         | 9.109        |
| bn100326402  | 09:33:30.596                  | -55.808                         | 32.512       |
| bn100424876  | 21:03:54.875                  | -123.791                        | 2.521        |
| bn100517154  | 03:42:30.304                  | -22.365                         | 1.362        |
| bn100601901  | 00:22:24.001                  | -77.870                         | 9.918        |
| bn100625891  | 21:22:58.362                  | -15.645                         | 4.029        |
| bn100706602  | 14:28:25.731                  | -56.254                         | 16.328       |
| bn100718160  | 03:50:13.287                  | -25.036                         | 6.090        |
| bn100718160  | 03:50:13.287                  | -7.415                          | 6.808        |
| bn100730463  | 11:06:50.220                  | -41.808                         | 12.805       |
| bn100730463  | 11:06:50.220                  | -18.243                         | 0.001        |
| bn100827455  | 10:55:49.710                  | -0.442                          | 0.079        |
| bn100923844  | 20:15:31.462                  | -24.128                         | 4.019        |
| bn110030664  | 15:56:24.411                  | -69.697                         | 31.744       |
| bn110224578  | 13:55:30.861                  | -33.455                         | 10.658       |
| bn110227536  | 12:51:49.785                  | -3.895                          | 3.646        |
| bn110227888  | 18:55:41.740                  | -67.434                         | 25.256       |
| bn110227229  | 05:30:09.611                  | -111.145                        | 21.120       |
| bn110428338  | 08:07:18.821                  | -70.448                         | 42.874       |
| bn110428338  | 08:07:18.821                  | -18.748                         | 13.308       |
| bn110528624  | 14:59:12.297                  | -217.477                        | 11.744       |
| bn110528624  | 14:59:12.297                  | -35.653                         | 13.654       |

Continued on next page
Table I continued: Temporal properties of the identified precursors.

| GRB               | $t_{\text{prompt}}$ (UTC) | $t_{\text{precursor}}$ (s) | Duration (s) |
|-------------------|-----------------------------|----------------------------|--------------|
| bn110725236       | 05:39:57.932               | -16.720                    | 7.619        |
| bn110729142       | 03:30:47.288               | -342.504                   | 52.731       |
| bn110729142       | 03:30:47.288               | -185.188                   | 51.556       |
| bn110825102       | 02:26:58.702               | -7.864                     | 8.014        |
| bn110903111       | 02:42:41.533               | -187.466                   | 22.062       |
| bn110904124       | 02:58:55.085               | -44.632                    | 7.665        |
| bn110909116       | 02:47:01.914               | -4.433                     | 1.670        |
| bn110926107       | 02:34:30.183               | -45.717                    | 3.110        |
| bn111010709       | 17:01:07.319               | -34.749                    | 31.018       |
| bn111015427       | 10:15:22.011               | -25.770                    | 17.144       |
| bn111228657       | 15:45:16.506               | -46.111                    | 10.496       |
| bn111230683       | 16:23:06.415               | -11.301                    | 4.631        |
| bn111230819       | 19:39:41.521               | -9.814                     | 1.304        |
| bn111230819       | 19:39:41.521               | -8.120                     | 4.234        |
| bn120118709       | 17:00:24.779               | -6.498                     | 5.475        |
| bn120305888       | 14:06:05.511               | -21.363                    | 3.092        |
| bn120319983       | 23:35:18.709               | -17.629                    | 5.551        |
| bn120412920       | 22:05:51.344               | -71.057                    | 5.502        |
| bn120504945       | 22:40:07.713               | -1.369                     | 0.799        |
| bn120513531       | 12:44:14.932               | -15.008                    | 1.330        |
| bn120530121       | 02:54:31.969               | -50.475                    | 7.974        |
| bn120611108       | 02:35:54.181               | -8.321                     | 6.602        |
| bn120710100       | 02:25:09.865               | -113.086                   | 4.857        |
| bn120711115       | 02:45:52.633               | -61.735                    | 4.838        |
| bn120716712       | 17:08:00.170               | -176.365                   | 5.383        |
| bn120819048       | 01:09:20.076               | -60.316                    | 7.618        |
| bn120819048       | 01:09:20.076               | -30.405                    | 1.638        |
| bn121005340       | 08:10:54.001               | -101.730                   | 38.794       |
| bn121029350       | 08:24:27.774               | -11.090                    | 8.798        |
| bn121031949       | 22:50:21.029               | -191.769                   | 38.495       |
| bn121113544       | 13:03:25.589               | -45.362                    | 31.652       |
| bn121125356       | 08:32:50.026               | -29.374                    | 20.325       |
| bn121217313       | 07:29:53.089               | -714.103                   | 65.792       |
| bn130104721       | 17:18:12.706               | -5.969                     | 3.898        |
| bn130106995       | 23:52:56.117               | -33.325                    | 17.558       |
| bn130208684       | 16:24:43.858               | -21.975                    | 5.099        |
| bn130209961       | 23:03:46.502               | -101.730                   | 38.794       |
| bn130219775       | 18:36:47.745               | -56.310                    | 20.260       |
| bn130310840       | 20:09:45.591               | -4.755                     | 1.194        |
| bn130318456       | 10:57:50.305               | -82.735                    | 6.897        |
| bn130320560       | 13:29:06.051               | -159.315                   | 42.085       |
| bn130404840       | 20:10:25.030               | -21.354                    | 8.355        |
| bn130418444       | 20:16:08.506               | -87.313                    | 16.452       |
| bn130504314       | 07:32:36.037               | -32.672                    | 0.464        |
| bn130623130       | 03:07:03.470               | -26.744                    | 1.821        |
| bn130720582       | 13:59:15.940               | -146.139                   | 115.366      |
| bn130813791       | 18:59:18.842               | -5.810                     | 1.680        |
| bn130815660       | 15:51:22.993               | -31.482                    | 6.925        |
| bn130818941       | 22:34:29.441               | -70.463                    | 8.706        |
| bn130919173       | 04:09:40.924               | -0.686                     | 0.236        |
| bn131014513       | 12:18:34.911               | -20.917                    | 2.089        |
| bn131008204       | 00:34:43.981               | -2.395                     | 1.815        |
| bn140104731       | 17:34:01.991               | -120.439                   | 66.204       |
| bn140104731       | 17:34:01.991               | -24.501                    | 1.459        |
| bn140108721       | 17:19:53.720               | -71.900                    | 11.570       |
| bn140206815       | 19:33:40.215               | -62.234                    | 20.478       |
| bn140304515       | 19:33:40.215               | -24.385                    | 14.110       |
| bn140304849       | 20:25:37.760               | -189.609                   | 30.654       |
| bn1403209295      | 07:04:57.833               | -19.534                    | 0.630        |
Table I continued: Temporal properties of the identified precursors.

| GRB             | $t_{prompt}$ (UTC) | $t_{precursor}$ (s) | Duration (s) |
|-----------------|---------------------|---------------------|--------------|
| bn140404030     | 00:43:22.825        | -71.917             | 7.657        |
| bn140512814     | 19:33:23.687        | -98.421             | 11.788       |
| bn140621827     | 19:50:14.988        | -4.111              | 0.718        |
| bn140628704     | 16:54:21.456        | -66.005             | 4.910        |
| bn140709051     | 01:13:51.906        | -11.397             | 5.700        |
| bn140742686     | 06:27:35.035        | -109.468            | 27.544       |
| bn140716436     | 10:29:26.513        | -89.084             | 2.218        |
| bn140818229     | 05:31:17.613        | -69.604             | 10.233       |
| bn140824606     | 14:34:24.964        | -73.928             | 12.933       |
| bn140825328     | 07:53:42.446        | -59.289             | 11.821       |
| bn140825328     | 07:53:42.446        | -38.258             | 3.215        |
| bn140917512     | 12:17:10.292        | -4.343              | 3.940        |
| bn141029134     | 03:14:24.675        | -66.449             | 3.739        |
| bn11029134      | 03:14:24.675        | -41.574             | 6.940        |
| bn14102536      | 12:51:40.741        | -1.269              | 0.088        |
| bn150126868     | 20:51:32.131        | -55.037             | 13.019       |
| bn150127398     | 09:32:49.909        | -6.512              | 5.747        |
| bn150226545     | 13:08:44.224        | -202.152            | 1.028        |
| bn150226545     | 13:08:44.224        | -155.467            | 7.878        |
| bn150226545     | 13:08:44.224        | -41.188             | 16.158       |
| bn150330828     | 19:53:59.254        | -98.194             | 11.412       |
| bn150416773     | 18:33:22.811        | -824.534            | 42.496       |
| bn150522703     | 16:52:31.997        | -468.581            | 15.616       |
| bn150506398     | 09:33:46.679        | -116.285            | 27.791       |
| bn150508945     | 22:40:36.620        | -102.265            | 15.712       |
| bn150512432     | 10:23:46.759        | -86.467             | 43.029       |
| bn150512432     | 10:23:46.759        | -28.503             | 20.212       |
| bn150524333     | 10:24:07.264        | -19.511             | 7.822        |
| bn150523296     | 09:30:14.993        | -28.370             | 19.748       |
| bn150627183     | 04:23:22.017        | -458.665            | 3.072        |
| bn150709998     | 23:56:45.108        | -6.691              | 2.490        |
| bn150705314     | 03:33:54.082        | -13.280             | 0.008        |
| bn150830128     | 03:04:38.646        | -14.638             | 14.021       |
| bn151027166     | 04:00:00.254        | -96.360             | 40.571       |
| bn151030999     | 23:59:47.634        | -88.314             | 17.686       |
| bn151216172     | 16:07:28.188        | -151.405            | 26.022       |
| bn160131174     | 04:12:52.609        | -179.691            | 44.007       |
| bn160201883     | 21:11:44.177        | -1.590              | 0.968        |
| bn160215773     | 18:36:08.605        | -109.239            | 44.645       |
| bn160219673     | 16:11:34.712        | -110.393            | 12.546       |
| bn160223072     | 01:45:54.364        | -95.615             | 10.496       |
| bn160225809     | 19:25:09.731        | -48.115             | 23.215       |
| bn160521299     | 04:45:57.662        | -56.663             | 9.377        |
| bn160519012     | 00:18:55.054        | -83.260             | 3.345        |
| bn160519012     | 00:18:55.054        | -65.164             | 17.101       |
| bn160523919     | 22:04:13.977        | -38.410             | 5.424        |
| bn160625945     | 22:43:14.909        | -78.317             | 2.418        |
| bn160724444     | 10:40:02.521        | -78.317             | 1.790        |
| bn160821857     | 20:36:22.642        | -117.067            | 31.832       |
| bn160825799     | 19:10:50.313        | -1.449              | 0.599        |
| bn160908136     | 03:16:48.679        | -87.733             | 6.845        |
| bn160912521     | 12:31:42.840        | -57.422             | 36.635       |
| bn160912521     | 12:31:42.840        | -17.072             | 5.193        |
| bn160919613     | 14:43:36.685        | -24.729             | 0.496        |
| bn160919613     | 14:43:36.685        | -15.327             | 0.761        |
| bn161054117     | 10:01:18.575        | -30.217             | 12.749       |
| bn161111197     | 04:45:50.635        | -102.553            | 11.125       |
| bn161110666     | 01:37:14.177        | -103.474            | 77.027       |
| bn161119633     | 15:11:02.131        | -10.916             | 7.666        |
| bn161129000     | 07:11:45.292        | -5.373              | 0.040        |

Continued on next page
Table I continued: Temporal properties of the identified precursors.

| GRB         | \(t_{\text{prompt}}\) (UTC) | \(t_{\text{precursor}}\) (s) | Duration (s) |
|-------------|-------------------------------|-------------------------------|--------------|
| bn170109137 | 03:21:41.186                 | -245.940                      | 18.163       |
| bn170109137 | 03:21:41.186                 | -217.040                      | 6.377        |
| bn170115662 | 15:54:01.580                 | -95.287                       | 18.563       |
| bn170209048 | 01:09:05.007                 | -28.188                       | 8.228        |
| bn170323775 | 18:36:31.186                 | -12.963                       | 12.697       |
| bn170402961 | 23:03:40.777                 | -15.936                       | 1.501        |
| bn170416583 | 14:00:34.755                 | -35.298                       | 12.494       |
| bn170514152 | 03:38:43.989                 | -5.895                        | 0.678        |
| bn170514180 | 04:19:54.177                 | -79.666                       | 35.908       |
| bn170830069 | 01:38:59.546                 | -19.395                       | 5.987        |
| bn170831179 | 04:18:03.061                 | -73.621                       | 8.547        |
| bn170831179 | 04:18:03.061                 | -43.400                       | 6.309        |
| bn170832315 | 04:31:15.015                 | -10.012                       | 1.018        |
| bn171004857 | 20:33:34.433                 | -29.516                       | 10.393       |
| bn171122107 | 02:34:03.231                 | -198.952                      | 8.192        |
| bn171122868 | 20:50:13.004                 | -43.928                       | 9.502        |
| bn171211844 | 13:20:33.596                 | -31.460                       | 4.221        |
| bn171211844 | 20:17:18.932                 | -82.541                       | 12.393       |
| bn180124392 | 09:23:59.613                 | -4.987                        | 0.611        |
| bn180124392 | 02:16:29.991                 | -820.685                      | 11.776       |
| bn180307073 | 01:44:35.183                 | -39.275                       | 23.342       |
| bn180411519 | 12:28:28.650                 | -54.086                       | 26.673       |
| bn180416340 | 08:10:01.701                 | -36.541                       | 10.291       |
| bn180426549 | 13:10:59.907                 | -13.182                       | 5.544        |
| bn180618724 | 17:22:55.701                 | -61.611                       | 26.238       |
| bn180620354 | 08:29:22.735                 | -72.842                       | 5.855        |
| bn180710062 | 01:29:21.269                 | -49.933                       | 13.542       |
| bn180720598 | 14:21:26.039                 | -29.189                       | 10.000       |
| bn180728728 | 17:29:14.137                 | -15.219                       | 10.040       |
| bn180822423 | 10:08:32.522                 | -5.898                        | 2.803        |
| bn180822562 | 13:30:39.570                 | -128.070                      | 7.513        |
| bn180822562 | 13:30:39.570                 | -118.178                      | 6.344        |
| bn180906988 | 23:42:36.388                 | -2.471                        | 1.039        |
| bn180929453 | 10:52:35.121                 | -1.456                        | 0.606        |
| bn181007385 | 09:14:19.608                 | -23.373                       | 3.996        |
| bn181008877 | 21:04:29.161                 | -131.183                      | 27.879       |
| bn181119060 | 14:32:19.202                 | -2.566                        | 1.798        |
| bn181122381 | 09:09:04.964                 | -1.937                        | 0.299        |
| bn181203880 | 21:06:37.705                 | -6.482                        | 0.870        |
| bn181222279 | 06:42:52.975                 | -79.631                       | 40.808       |
| bn190114873 | 20:57:02.490                 | -5.573                        | 1.942        |
| bn190114873 | 20:57:02.490                 | -2.854                        | 1.537        |
| bn190205938 | 22:31:11.876                 | -40.086                       | 9.198        |
| bn190228973 | 23:21:30.204                 | -15.148                       | 7.989        |
| bn190310398 | 09:33:20.756                 | -49.157                       | 4.120        |
| bn190315512 | 12:17:39.138                 | -366.193                      | 6.912        |
| bn190323879 | 21:05:17.600                 | -893.855                      | 26.624       |
| bn190324947 | 22:44:18.392                 | -17.146                       | 2.474        |
| bn190326314 | 07:32:13.823                 | -27.769                       | 1.672        |
| bn190326314 | 07:32:13.823                 | -18.099                       | 2.115        |
| bn190610750 | 18:00:04.042                 | -14.819                       | 1.160        |
| bn190611950 | 22:48:51.696                 | -62.594                       | 20.082       |
| bn190719624 | 15:00:01.045                 | -86.830                       | 1.579        |
| bn190806675 | 16:12:34.836                 | -1.664                        | 1.188        |
| bn190808142 | 12:59:58.210                 | -46.588                       | 38.596       |
| bn190809830 | 19:56:40.582                 | -47.965                       | 5.565        |
| bn190901890 | 21:21:37.555                 | -63.144                       | 20.014       |

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Table I continued: Temporal properties of the identified precursors.

| GRB      | $t_{prompt}$ (UTC) | $t_{precursor}$ (s) | Duration (s) |
|----------|--------------------|---------------------|--------------|
| bn190930400 | 09:38:17.809       | -162.830            | 40.308       |
| bn191019970 | 23:18:48.942       | -96.333             | 29.779       |
| bn191026350 | 08:23:43.801       | -5.943              | 4.110        |
| bn191031025 | 00:39:28.692       | -178.171            | 10.422       |
| bn191101895 | 21:28:37.561       | -44.664             | 1.903        |
| bn191111364 | 08:44:52.025       | -25.765             | 16.425       |
| bn191225309 | 07:26:50.763       | -94.689             | 2.024        |