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Review

Gamma-Ray Bursts at TeV Energies: Observational Status

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Abstract: Gamma-ray bursts (GRBs) are some of the most energetic events in the Universe and are potential sites of cosmic ray acceleration up to the highest energies. GRBs have therefore been a target of interest for very high energy gamma-ray observatories for many years, leading to the recent discovery of a number of bursts with photons reaching energies above 100 GeV. We summarize the GRB observational campaigns of the current generation of very high energy gamma-ray observatories as well as describing the observations and properties of the GRBs discovered so far. We compare the properties of the very high energy bursts to the total GRB distribution and make predictions for the next generation of very high energy gamma-ray observations.

Keywords: gamma-ray bursts; VHE gamma-rays; IACTs

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1. Introduction

The origins of gamma-ray bursts have been a mystery since their discovery in the 1960s. As the name suggests, the definition was an unknown phenomenon, rather than an astronomical object, a short pulse seen in gamma-ray bands ($>\sim$100 keV) detected by the Vela gamma-ray detection satellites [1]. After this early detection, tremendous efforts were devoted to this research field for several decades. We have come to know that GRBs are extra-Galactic phenomena, occurring isotropically over the sky at any time, with a variety of properties in time and energy. In addition, it became clear that there are multiple classes in this object, whose origins are different. Either class of bursts has a short pulse of gamma-/X-rays called "prompt" emission, followed by a quickly fading "afterglow" detected in a wider waveband (See Granot and Gill in this special issue for more details on GRB physics).

Deeper insights into the origin and phenomenology of GRBs were made by dedicated detectors placed on satellites, such as BATSE [2] on board the Compton gamma-ray observatory (CGRO) and HETE-2 [3]. These instruments confirmed the extragalactic origin of the bursts [4], a clearly bimodal distribution in their emission timescales [5] and a characteristic spectral shape [6]. The Neil Gehrels Swift Observatory (Swift [7]) was launched in 2004 and made a big step toward the full understanding of GRBs. The Swift observatory has three instruments named the Burst Alert Telescope (BAT), X-ray Telescope (XRT) and UltraViolet/Optical Telescope (UVOT). The Swift-BAT is sensitive in 15–150 keV energies, and has the ability to localize the direction of the incoming gamma rays, typically with an error of a few arcmin. This small localization error enables other telescopes on the Earth and onboard to repoint and observe the burst without any ambiguity. In order to organize a quick response all over the world, a network called Gamma-ray Coordination Network (GCN) system is established [8]. The GCN sends to subscribed astronomers a series of packets and emails containing the coordinates and other properties of the detected GRBs. The typical delay from the onset of the burst to the arrival of information is short, typically taking around 20 s. The bunch of information is called "alert", meant to trigger a quick response ("follow-up") of those following the alert system. A large part of the success in the Swift era can be attributed to such follow-up observations by the optical/infrared/radio telescopes. The studies revealed a big picture, such as the mechanism of the afterglow and properties of typical host galaxies, and confirmed the classification by the burst duration that was suggested by BATSE. Properties of the afterglow such as flares and plateau phase found in X-rays remained a mystery.

There are other satellites that contribute to sending their GRB alerts. Among them, one of the most active satellites is the Fermi Gamma-ray Space Telescope (Fermi) launched in 2008. It has two instruments called Gamma-ray Burst Monitor (GBM [9]) and Large Area Telescope (LAT [10]). The Fermi-GBM is sensitive from a few keV to $\sim$MeV, and has a 4π field of view with a localization error of up to 15 degrees. The Fermi-GBM increased the number of detected GRBs roughly to once every 2 days (from once every 5–7 days in the Swift era), and enabled statistical studies of thousands of GRBs [11]. However, the remaining uncertainties such as the mechanism of the prompt emission, and the origin of the central engine, have been a mystery even in the Fermi era. Indeed, the increase of the number of GRBs revealed further unknowns, in particular, in the GRB classification (e.g., [12]).

The Fermi-LAT is a pair conversion telescope sensitive to MeV-GeV gamma-rays, with a field of view of around 0.5 steradians. The Fermi-LAT confirmed the existence of GeV-emitting GRBs [13] that were suggested by the predecessor EGRET telescope, and investigated their emission properties in detail. It has been found that the GeV gamma-ray emission is often observed with a delay of (typically) about 1–10 s after the burst onset. For a few GeV GRBs, gamma rays with energy of tens of GeV were detected even hours after the burst, which challenges the standard model of the relativistic particle acceleration. To push beyond the 100 GeV energy limit, a satellite instrument such as Fermi has difficulty detecting gamma rays due to its limited collection area (about 1 m^2). These energies are instead within the reach of imaging atmospheric Cherenkov telescopes (IACTs), which have an orders of magnitude larger effective detection area. However, it should be noted that an ultimate high energy limit is placed on the detection of distant photons due to the absorption of photons by the predominantly infra-red extragalactic background light (EBL) [14]. EBL absorption becomes more important as both energy and source distance increase, causing an attenuation of energetic photons to have a steepening effect on the source spectrum. Therefore, it has long been expected that IACTs could detect nearby and bright GRBs and contribute to further understanding the GRB phenomena.

2. Observation Schemes

The current generation of IACTs has been hugely successful in transforming the field of VHE gamma-ray astronomy from a field with only a handful of sources detected to over 200 [15]. Significant effort has been invested over several generations of IACT instruments to perform rapid transient source follow ups with, optimising for high sensitivity to steep spectrum sources. A major focus for transient observations in these instruments is placed on GRBs, in parallel to very similar observation programs for related sources such as gravitational wave and VHE neutrino triggers. The sensitivity of the three current instruments is roughly similar, being around three to four orders of magnitude better than that of the Fermi-LAT for an observation time shorter than 10^4 s [16].

2.1. H.E.S.S.

The High Energy Stereoscopic System (H.E.S.S.) is an array of five imaging atmospheric Cherenkov telescopes located in the Khomas highlands of Namibia (approx. 23.5° latitude) at an altitude of 1800 m. The H.E.S.S. array is composed of four 12 m diameter telescopes (approx. 100 m^2 mirror area) in a square of 12 m side length with a 28 m telescope (approx. 600 m^2 mirror area) at the array center with an energy threshold as low as 40 GeV. The differential sensitivity of the system is estimated below 1% of the Crab Nebula flux above 300 GeV with a 50-h observation [17].

H.E.S.S. has maintained an active GRB observation campaign since its commissioning in 2004 [18], which received renewed focus in 2012 [19] with the completion of the large telescope (and subsequent lowering of the energy threshold). Trigger and observability criteria have been continuously adapted and improved over the lifetime of H.E.S.S. based on the experience of observations and the instruments available to trigger observations. The current observation scheme automatically monitors events from the GCN system and classifies them into two categories [20]. The first category being events immediately visible from the H.E.S.S. site at the time of the burst, or within 4 h, which are only subject to observability requirements, with any event visible above 60° zenith angle for more than 30 min being observed. Observation of these events is initiated automatically with no human input. The remaining bursts are subjected to requirements based on the source significance (specifically in the case of Fermi-GBM observations) and redshift (if known), with longer observation delays being allowed for nearer objects. However, any observation restrictions can be overridden by burst advocates in the case of confirmed high energy gamma-ray emission from the Fermi-LAT.

In the period from 2004 to 2019, H.E.S.S. observed a total of 96 GRBs [18,21] split between four telescope (32 observations) and five telescope data (64 observations).

2.2. MAGIC

MAGIC (Major Atmospheric Gamma Imaging Cherenkov telescopes) is a system composed of two imaging air Cherenkov telescopes, located at 2200 m above sea level, at the Roque de Los Muchachos Observatory in La Palma, Canary Islands, Spain. Both telescopes have a mirror diameter of 17 m, which enables a low energy threshold of above 30 GeV, depending on the observing mode and conditions, with a field of view of $\sim$10 square degrees. The integral sensitivity of the system is 0.66% of the Crab Nebula flux above 220 GeV with a 50-h observation [22].

The telescopes were designed to perform fast follow-up observations of GRBs. Their structure is made of light-weight carbon-fiber-reinforced polymer tubes, and their drive system has a special fast slewing mode with a speed of 7 deg/s. To reduce the latency in performing GRB observations, MAGIC implemented a fully automatic reaction to alerts through its automatic alert system (AAS). AAS is a multi-threaded program that receives GCN notices containing the sky coordinates, filters them with predefined conditions, and sends commands to the central control software of the telescopes when needed. The AAS also includes a check of new targets according to a predefined priority. If multiple alerts are received for a single GRB, AAS selects the one with the best localization. Once the commands are sent to the central control software, it issues the following commands to the telescope subsystems such as drive, camera control, and DAQ, in order to slew and start to observe the GRB as early as possible.

The predefined conditions to trigger observations are the zenith angle less than 60 degrees, Moon distance larger than 30 degrees, and Sun distance larger than 103 degrees. The observation up to 4 h after T_0 is triggered automatically if the above conditions are met (Note that this criteria is updated after 2019 to allow more late time observations). In the period from 2005 (from 2013 after the major upgrade) to 2019, MAGIC observed a total of 107 (50) GRBs [23].

2.3. VERITAS

VERITAS [24] consists of an array of four 12-m imaging atmospheric Cherenkov telescopes located at the Fred Lawrence Whipple Observatory in southern Arizona, USA, at 1300 m above sea level. Each of the telescopes is equipped with a camera of PMTs covering a field of view (FoV) of 3.5 degrees. The system has maximum sensitivity in the energy range of 100 GeV to 30 TeV. The angular resolution is $\sim$0.1 degrees at 1 TeV and the energy resolution is 15–25% at 1 TeV. The current system can detect a source (5σ significance) with 1% of the Crab Nebula flux in 25 h [25].

VERITAS is subscribed to the GCN and has integrated an automated tracking response from incoming GCN alerts. The alerts are quickly parsed and reviewed by onsite operators, who assess visibility and observable conditions (such as pointing direction, slew time, and weather) and decide to follow up the alert.

VERITAS has followed up more than 200 GRBs since the beginning of its GRB program in 2006 [26].

2.4. Other Instruments

This review concentrates primarily on the VHE GRB detections made by the current generation of IACTs (and the prospects for the future Cherenkov telescope array [27]). However, a new generation of sensitive wide field of view (wFOV) ground-based gamma-ray telescopes maintain strong GRB observation programs. wFOV gamma-ray instruments typically use ground based particle detectors (e.g., HAWC [28] & Tibet-ASγ [29]), sometimes in combination with wide field Cherenkov light detectors (e.g., LHAASO [30]). This detection technique typically has a higher energy threshold and reduced sensitivity in comparison to IACTs. However, the large field of view ($\sim$2 steradian) of these detectors make them much more likely to catch the GRB during its prompt phase. Eventually, these detectors might even provide triggers to IACTs on top of those from satellites. This detector class therefore has strong potential to extend the number of detected GRBs beyond that seen by the IACTs, potentially into time frames which are difficult or even impossible to access with Cherenkov telescopes.

3. Status of Detected GRBs

The observation programs of the current generation of VHE gamma-ray observatories in the previous sections have been performed for many years and have been able to provide useful upper limits and constraints on the VHE gamma-ray emission of GRBs [18,31–36]. However, in the last few years, several GRB detections have been made around 100 GeV. In this section, we will describe the observations of these detected events and the major findings from their analysis.

3.1. GRB 180720B

GRB 180720B was first detected by the Swift-BAT on 20 July 2018, 14:34:56 UT (T_0) [37]. This GRB was relatively bright in X-ray emission in the prompt phase and long with a characteristic timescale of 90% of gamma-ray emission (T_{90}) of $\sim$49 s [38], classifying it as a long GRB. In the following hours, the fading of the prompt emission revealed an extremely bright X-ray afterglow [38], second only in brightness to the extreme GRB 130427A. A detection of the GRB by the Fermi-LAT and GBM followed around 10 h later, with a maximum photon energy of 5 GeV being detected [39]. Numerous optical observations of the afterglow resulted in the measurement of a redshift by the VLT/X-Shooter of 0.654 [40] around 19 h after burst time.

At the time of the GRB prompt emission, GRB 180720B was not visible from the H.E.S.S. site, only becoming observable above the typical 45 degree zenith angle threshold used by H.E.S.S. until T_0 + 10.1 h [41]. In total, around two hours of observations were made before observations were ended. When a full mono analysis of these data was later performed, a clear signal at 5.3σ was seen at a position consistent with the location of the GRB. By this time, the GRB observations from the H.E.S.S. site were no longer possible and follow-up observations were made at T_0 + 18 days, with no source being seen at this position.

The observed spectrum extracted in the energy range 100 GeV to 440 GeV was fit with a power law and found to be extremely steep, with a spectral index of -3.7, explaining why the event was seen only in the low energy optimized *mono* analysis. After correcting the data for the absorption of energetic photons by the extragalactic background light [14], a rather hard spectral index of -1.6 ± 1.2 was extracted. This hard index is consistent with the value of -2 seen in both X-ray and gamma-ray data, but with a rather large uncertainty due to the relatively narrow energy range in which the spectrum could be fit.

3.2. GRB 190114C

GRB 190114C was identified by Swift-BAT and Fermi-GBM on 14 January 2019, 20:57:03 UT (T_0). Its duration in terms of T_{90} was $\sim$116 s by Fermi-GBM [42] and $\sim$362 s by Swift-BAT [43], both of which indicate that it can be classified as a long GRB. Its afterglow emission is reported by various instruments from 1.3 GHz to 23 GeV, and its redshift is reported to be $z = 0.4245 \pm 0.0005$ [44,45]. The isotropic-equivalent energy of the emission at energy of 1–10^4 keV was $E_{\rm iso} \approx 3 \times 10^{53}$ erg by Fermi-GBM. The GRB was more energetic then the average but not exceptional.

The observation by MAGIC started from T_0 + 57 s until T_0 + 15,912 s in good weather but with a bright moonlight and high zenith angle over 55 degrees. Nevertheless, the detection above 0.2 TeV in the first 20 min was reported by MAGIC through GCN [46] and ATel [47], which was just 4 h after the burst based on the result of a quick online analysis. It was the first announcement of a GRB detection with IACTs ever. Fermi-LAT observations confirmed that the detected emission is from the afterglow phase of the GRB, even at T_0 + 57 s [48]. The light curve obtained by MAGIC is decaying monotonically mostly following the X-ray observations. It suggested that the amount of energy conveyed by VHE gamma rays is close to one in X-rays. The obtained spectrum shows a single power-law with a slope of index -2.2 after the spectrum corrected for EBL absorption, extending even to multi-TeV energies [49]. The multi-wavelength (MWL) study with 23 instruments showed that the MWL spectrum can be well modeled with the synchrotron self-Compton (SSC) emission, and that the VHE gamma-ray emissions is consistent with the estimation with SSC [50].

3.3. GRB 190829A

GRB 190829A was initially detected by the Fermi-GBM on 29 August 2019 at 19:55:53 UT [51] and was classified as a long GRB ($T_{90} = 63$ s), soon after being detected by the Swift-BAT and XRT [52,53]. The X-ray light curve showed an interesting structure with multiple re-brightening events, most notably significantly increasing in brightness around 1000 s after burst time. Due to the bright nature of this burst, multiple ground based optical observations were made, allowing the identification of the GRB host galaxy [54] and ultimately measuring the GRB redshift at a relatively very local $z = 0.0785 \pm 0.0005$. Although this GRB was very bright, its brightness was largely due to its relative closeness and in fact was of rather low luminosity and had an isotropic energy release of only around 2×10^{50} erg.

Observations with the H.E.S.S. array began 4 h after the burst, with a significant signal being detected for three consecutive observation nights (until 56 h after burst time) [55]. The intrinsic source spectrum was extracted using data from the four 12 m telescopes, with a best fit power law index of -2.06 ± 0.1 on night one (in the energy range from 180 GeV to 3.3 TeV) and -1.86 ± 0.26 on night two, the significance of night 3 observations was too low to extract a reliable spectrum. Again, the recovered index was consistent with that seen in X-ray measurements both in index and flux level. The gamma-ray energy flux over the course of the observations was seen to decrease with a time decay index of 1.09 ± 0.05, consistent with the X-ray temporal decay.

Modeling of this GRB by the H.E.S.S. collaboration shows difficulties with reproducing the source spectrum using the conventional one zone SSC model [55]. Instead, they propose a synchrotron emission model; however, one must explain here the extension of the emission beyond the typical maximum synchrotron energy.

3.4. GRB 201216C

GRB 201216C is a long GRB triggered by the Swift-BAT on 16 December 2020, 23:07:31 UT (T_0) [56]. Its prompt emission with multiple peaks lasted for about 48 s in terms of T_{90} measured by Swift-BAT [57], and 29.9 s by Fermi-GBM [58], both of which clearly classified it as a long GRB. Its redshift is estimated to be z = 1.1 by the optical observations with the ESO Very Large Telescope [59]. The isotropic-equivalent energy of the emission at energy of 10–10^3 keV was $E_{\rm iso} \approx 4.7 \times 10^{53}$ erg with the fluence measured by Fermi-GBM.

MAGIC started to observe it at T_0 + 56 s, until 2.2 h after the burst. The zenith angle of the observation ranged from 37 to 68 deg, in good weather on a moonless night, which made possible the analysis of the data with an energy threshold below 100 GeV (changing w.r.t the zenith angle). MAGIC detected the gamma rays with a significance of 5.9 sigma from the first 20 min of the observation [60,61]. The light curve obtained from the first 20 min (with an energy threshold of 70 GeV) was monotonically decaying, and the spectrum from the first 20 min is consistent with a power-law extended from 50 GeV to 200 GeV [61].

4. Sub Threshold GRB Detections

In addition to the GRBs passing the typical $5\,\sigma$ significance threshold, there are several bursts which show lower significance hints of emission. Although these bursts should be treated with caution, they may contain hints of the physics of VHE gamma-ray emission in some classes of GRBs.

4.1. GRB 160821B

GRB 160821B is a short GRB triggered by the Swift-BAT on 21 August 2016, 22:29:13 UT (T_0). Its prompt emission was a short-decaying pulse with a duration of 0.48 s in terms of T_{90} measured by Swift-BAT [62], while about 1 s by Fermi-GBM [63]. A host galaxy is identified at redshift $z = 0.16$ by the Nordic Optical Telescope [64], which made it one of the nearest short GRBs. The isotropic-equivalent energy of the emission at energy of 10–10^3 keV (measured by GBM [63]) was $E_{\rm iso} \approx 1.2 \times 10^{49}$erg.

MAGIC started to observe it 24 s after its onset, with the zenith angle of 34 deg up to 55 deg until 4 h after T_0. The observations were carried out under a strong moon light and adverse weather, which made the energy threshold higher than the typical value. Nevertheless, a hint of gamma-ray emission is obtained with a significance of 2.9 sigma (post-trial) above 0.5 TeV [65]. The energy flux was estimated in a range of 0.5–5 TeV and compared with a detailed multi-wavelength model. The emission from radio to X-ray bands are modeled with the forward shock, the reverse shock, and also the kilonova emission that was reported later in 2019 [66,67]. Based on the physics parameters obtained in the above modeling, the flux in the TeV band was estimated with a Synchrotron self-Compton model. However, the putative flux by MAGIC is about an order of magnitude higher than the estimation by the model, which suggests a possibility of other explanations for the TeV emission, such as the external Compton scattering [65].

4.2. GRB 201015A

GRB 201015A was detected by the Swift-BAT on 15 October 2020, 22:50:13 UT (T_0) [68]. The duration of the prompt emission in terms of T_{90} is 9.8 s in the 15–350 keV band, from which the classification was not clear yet due to a complex light curve with a short pulse with a longer tail. The fluence in the 15–150 keV band is 2.0×10^{-7} erg/cm^2 [69]. The redshift of the burst was reported by GTC to be $z = 0.426$ [70], later confirmed by the NOT to be $z = 0.423$ [71]. The isotropic equivalent prompt emission energy in the *Fermi*-GBM range is $E_{\rm iso} \approx 1.1 \times 10^{50}$erg [72]. Finally, a supernova component was identified in late optical observations, which confirmed its classification as a long GRB [73,74]

MAGIC started to observe it 33 s after the burst onset, which is one of the fastest among the GRB observations by MAGIC. It continued until 4 h later, with the zenith angle starting from 24 degrees to 48 degrees. Quick offline analysis showed a hint of gamma-ray signals from the GRB with a significance of $>3\sigma$, as reported in GCN [75]. Final offline analysis extracted with a putative flux (>140 GeV) is 0.7–4.0×10^{-11}/s/cm^2. Since its redshift is close to one of GRB 190114C, we can roughly expect its VHE gamma-ray flux from their $E_{\rm iso}$ values. GRB 201015A has $E_{\rm iso}$ 3 orders of magnitude less than GRB 190114C, which is consistent with the flux, which is 2.5 orders of magnitude less, roughly scaling with the $E_{\rm iso}$ values.

5. Characteristics of Observed GRBs

The observed GRBs are all somewhat different in their individual behavior, but there are some general themes that can be drawn from the four confirmed detections, which may aid future detection of gamma rays at very high energies. The first obvious similarity is that the four significantly detected GRBs are long GRBs (with T_{90} of 30 s or above), likely originating from massive star collapse. Figure 1 shows the brightness of the VHE GRBs in comparison to the distribution of gamma-ray fluences as measured by Swift-BAT [1] and the eleven hour X-ray flux measured by Swift-XRT. Firstly, it is clear from both distributions that the VHE GRBs are all relatively bright in the keV energy range, with GRBs 180720B, 190114C and 201216C lying in the top 1% of all prompt GRB fluences. Similarly, the VHE GRBs are also bright in comparison to the distribution of X-ray afterglow emission, especially the two GRBs observed in the deep afterglow phase (GRBs 180720B and 190829A).

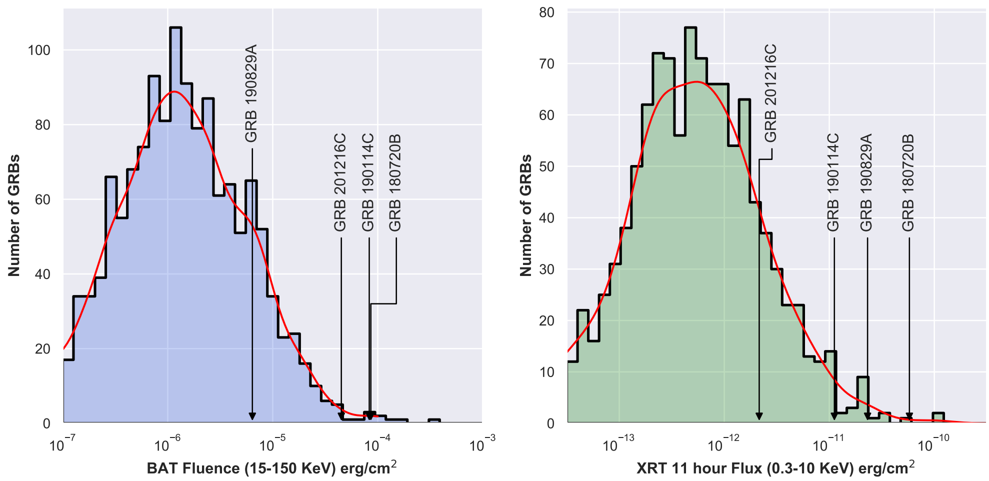

Figure 1. Distributions of the brightness of GRBs observed by Swift in the prompt and deep afterglow (11 h delay) phases. Brightness of the four VHE GRBs is marked on the *x*-axis. The red line displays the probability density of the distributions calculated by kernel density estimation.

The classification of the detected GRBs as both long and bright is likely dictated by instrumental constraints, with only the brightest GRBs being detectable given the relatively limited sensitivity of the current generation of Cherenkov telescopes and shorter events being difficult to detect due to their rapid fall off in brightness [76]. In addition, the brightness of the VHE burst and the correlations between the VHE gamma-ray and X-ray light curves implies that the lower energy gamma-ray and X-ray emissions represent a reasonable proxy for the gamma-ray brightness and could be used as a selection criteria for GRBs to be observed by VHE instruments.

This behavior is borne out in the comparison of X-ray lightcurves [2] shown in Figure 2 (left), with all four GRBs showing a similar brightness. However, GRB 190829A does shows a significant difference in the light curve behavior from the others, peaking more brightly, rapidly dimming and undergoing a re-brightening phase around 1000 s after the burst time. When representing the light curves as luminosity in Figure 2 (right), the nature of GRB 190829A as an outlier is even more clear, lying significantly below the other GRBs. The sub-threshold GRB 201015A shows a rather similar behavior to GRB 190829A but without the rebrightening; however, it should be noted that significant gaps are present in the Swift-XRT coverage of this burst (interpolated as a logarithmic decrease in Figure 2).

When combined with the redshift vs. isotropic energy output,[3] distribution plot shown in Figure 3 it becomes clear that the observed GRBs originate from two rather different distributions and represent different event classes. It has been proposed in literature that the brighter GRBs represent a distinct class of binary driven hypernovae (e.g., [77]), while GRB 190829A represents a low luminosity GRB (e.g., [78]); however, of course, with such a small number of events, such classifications remain speculative. Regardless of the physical processes involved within the GRB, it is clear that the GRB detections made by the current generation of Cherenkov telescopes are rather extreme events, skirting around the edges of the distribution of GRBs so far seen. Therefore, it should be considered that any conclusions drawn from this small event sample may not necessarily be representative of the majority of gamma-ray bursts. However, with increased instrument sensitivity, there is a clearly significant scope to vastly increase the number of VHE gamma-ray bursts detected.

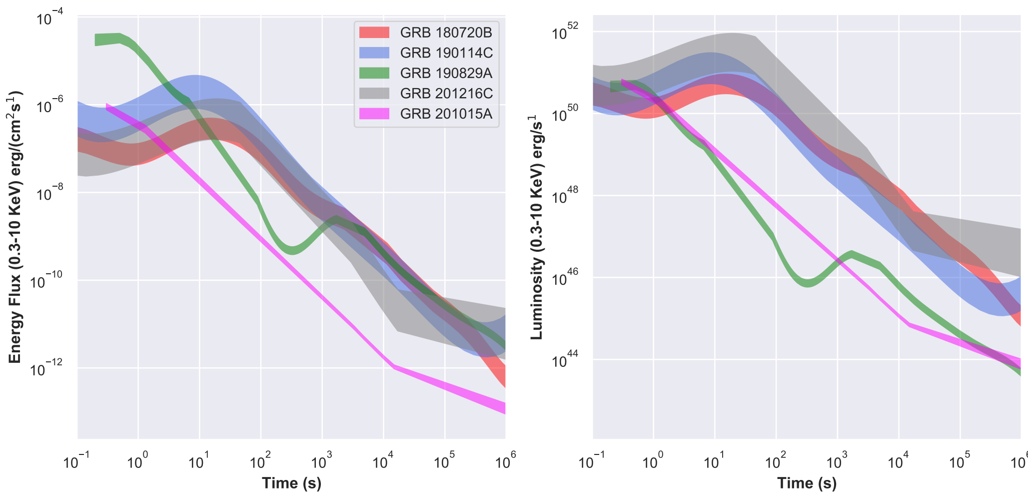

Figure 2. X-ray light curve of the four VHE GRBs shown as flux (**left**) and luminosity (**right**) using data from the Swift-BAT and XRT. Curves represent a smooth interpretation of the light curve evolution (using Gaussian processes); the width of the line gives an indication of the spread of data points. GRB 160821B is not shown in this plot because, as a short GRB, it is not directly comparable.

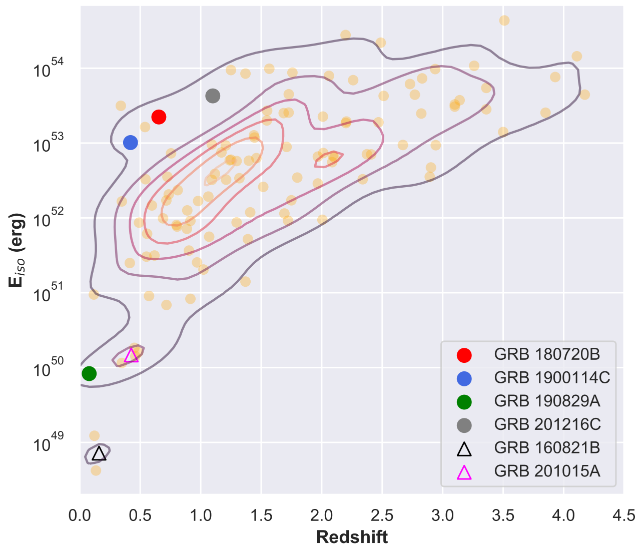

Figure 3. Distribution of the isotropic energy output of the GRBs (in the 50–300 keV range) versus the redshift. VHE GRBs are marked with the colored points (sub threshold GRBs are marked with open points), contours show the probability distribution calculated by kernel density estimation.

Finally, it is clear from Figure 3 that the sub-threshold GRB 160821B stands quite far apart from the main body of GRBs (with known redshift); however, this is to be expected due to its nature as a short GRB.

6. Conclusions and Prospects

This paper summarized the status of GRB observations by the IACTs that progressed tremendously in recent years. The instruments and observational strategies by those collaborations were briefly described, as well as the four clear and two more subthreshold GRB detections were explained in detail. The detection of these GRBs has proven the existence of emissions above 100 GeV at a flux level detectable by the relatively small instruments currently available. Although the number the detections is small, we have also tried to characterize the GRBs with VHE gamma-ray emissions in order to catch a glimpse of the hidden distribution behind the detected events. However, the detections made so far remain rather extreme bursts, on the edges of the distribution of events. We could not yet draw a clear conclusion if the detections are representing the majority of the GRBs.

Anyway, the detections have improved the observational strategies, and have also given insights into the emission mechanisms. The current generation of ground based gamma-ray telescopes all have active observation programs for gamma-ray bursts, and thus they will continue to regularly make observations of gamma-ray burst events for the years to come, expanding their observation programs to cover the several day timescales over which GRBs have been detected. Even though it is not the main scope of this paper, wFoV ground-based gamma-ray telescopes also have great potential to make a significant contribution in this field, by a synergy with the IACTs.

Within the decade, the next generation ground based gamma-ray observatory, the Cherenkov Telescope Array (CTA), should be completed [27]. CTA will combine multiple telescope types in both the northern and southern hemispheres to provide a sensitivity increase of an order of magnitude of the current telescope generation in the energy range from tens of GeV to hundreds of TeV. In particular, the large size (low energy optimised) telescopes are optimized for rapid repointing toward transient sources and should allow GRBs to be observed close to the burst time with significantly increased sensitivity. The large number of large and medium sized telescopes will also allow deep observations of GRBs in the afterglow regime. CTA observations will allow us to significantly increase the number of VHE detections, allowing the analysis of a much more representative sample of GRBs out to much longer timescales, greatly improving our understanding of particle acceleration within GRBs.

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Conflicts of Interest: The authors declare no conflict of interest.

Notes

[1] Data from https://swift.gsfc.nasa.gov/archive/grb_table/ [accessed on 2 September 2021].

[2] Data from https://www.swift.ac.uk/xrt_products/ [accessed on 23 December 2021].

[3] Data from https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html [accessed on 2 December 2021].

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