PROCEEDINGS OF SCIENCE

GRBs and their afterglows at VHEs

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Recently, the observational study of gamma-ray bursts (GRBs) in the very-high-energy (VHE) regime has advanced with several long-awaited detections with MAGIC, H.E.S.S., and LHAASO telescope systems. Currently, the list of GRBs with robustly measured VHE emissions contains GRB 180720B, GRB 190114C, GRB 190829A and GRB 221009A. Three more bursts were reported as source candidates by the MAGIC Collaboration. This candidate list includes a short GRB, which was detected with low significance (GRB 160821B), and a very distant GRB 201216C (from $z = 1.1$), which was detected with high significance ($> 5\sigma$). Detection of GRB afterglows in the VHE regime allows us to obtain essential information on particle acceleration by relativistic shock waves. This makes GRB afterglows important sources in high-energy astrophysics and their studies have an exceptionally broad scope. However, the extragalactic origin of GRB implies a severe constraint for their observational study in the VHE domain. Namely, the attenuation of multi-TeV photons by extragalactic background light (EBL) becomes significant at cosmological distances. The EBL absorption hardens the detection of GRBs and deforms their TeV spectrum, making nearly impossible any reliable determination of the intrinsic gamma-ray spectrum. The fortunate proximity of one of the detected GRBs (GRB 190829A occurred at $z \approx 0.08$) allowed an unexpectedly long signal detection, up to 56 hours after the trigger, and an accurate (and nearly independent on the specific EBL model) spectral determination in a broad energy interval, spanning from 0.18 to 3.3 TeV. The temporal and spectral properties of the VHE emission appeared to be remarkably similar to those seen in the X-ray band with Swift-XRT. Comparison to other detected GRB afterglow shows that SEDs and lightcurves obtained from GRBs share much in common. This disfavors the chances for GRB 190829A being an exceptional event, thus this case can be used as a standard event for testing afterglow models. Since many of the theoretical and numerical models fail to reproduce the hard powerlaw spectrum detected from GRB 190829A, this result may demand the need for a new generation of models used to predict the broadband emission from the GRB afterglows.

7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy (Gamma2022)
4-8 July 2022
Barcelona, Spain

https://pos.sissa.it/

PoS(Gamma2022)013

1. Introduction

Gamma-ray bursts (GRBs) were discovered serendipitously in 1967 by a military surveillance satellite, which was designed to search for nuclear tests in space. Using this instrument, one detected multiple flashes in the gamma-ray energy band with strange signatures. By localizing the flash origins, one excluded the terrestrial or solar origin. Later, it was shown that the directions to the GRB sources are isotropically distributed [1], implying their extragalactic origin. These discoveries started a completely new field of astronomy and astrophysics, which allowed studying extremely powerful cataclysmic events in the Universe.

The analysis of GRB light curves suggests that the event consists of two parts: prompt emission and afterglow phase. The prompt emission is associated with the operation of the central engine and the processes that occur inside the jet. The related electromagnetic radiation typically remains dominant during a relatively short initial period, lasting from a few to hundreds of seconds. Afterwards, the emission is dominated by the processes occurring at the forward shock that is launched in the circumburst medium: in the progenitor wind or interstellar medium (ISM). Based on the duration of the prompt phase, GRBs are divided into two classes [2], long GRBs and short GRBs. The duration of the delimitation of the prompt phase is selected to be 2 s. From a phenomenological point of view, the difference between long and short GRBs is related to the type of central engine. It is suggested that the long GRBs are generated by the collapse of massive stars [3, 4]. On the contrary, short GRBs are produced by the merger of binaries with compact companions [5].

The high bulk Lorentz factor of the outflows generated by GRBs, $\Gamma \sim 10^2$, Doppler boosts the GRB emission to higher energies, making them prominent gamma-ray sources. Fermi/LAT (Fermi Large Area Telescope) was able to detect about two hundred events [6], providing us with the light curves and spectra of many GRBs. However, despite detailed detection of multiple events and years of extensive study, the process of radiation and particle acceleration causing this radiation are not sufficiently well understood. The transient and non-repetitive nature of GRBs makes their understanding an extremely challenging task.

It was expected that detecting GRBs in the very-high-energy (VHE; > 100 GeV) should provide us with very important information on the physical conditions in the emission production region. These expectations are especially justified for the afterglow phase, during which the so-called synchrotron burn-off limit [7] allows ruling out the synchrotron origin of the VHE component. Indeed, synchrotron emission is expected to reach the VHE regime only if the bulk Lorentz factor is very high, $\Gamma \geq 10^3$, and such high bulk Lorentz factors are excluded during the afterglow phase by very robust arguments related to the hydrodynamic properties of the forward shock. For example, a self-similar solution for a relativistic blast wave [8] provides a very basic relation between the shock bulk Lorentz factor and the explosion energy. The revealed relation has an important implication: the bulk Lorentz factor depends very weakly on the model parameters, for example, in the case when the shock propagates through a homogeneous medium, one obtains $\Gamma \propto E_0^{1/8}$, where E_0 is the total isotropic energy of the explosion. This weak dependence allows us to rule out the case of $\Gamma \geq 10^3$ out by the available energy constraint.

Energy arguments also disfavor production of the VHE emission by a hadronic process at a level detectable with the current generation of gamma-ray instruments. The low density of the target for hadronic interactions (background protons for pp and hot photons for photomeson channels, respectively) during the afterglow phase implies a flux level of the emission generated through the hadronic channels at a presently undetectable level (for details, see, e.g., the discussion in Ref. [9]). These arguments make inverse Compton the most feasible radiation channel for the production of VHE emission, which can be detected during the GRB afterglows. Since the emission detected in X-ray and high energy (HE; $> 100\,\mathrm{MeV}$) has most like the synchrotron origin [10], detection of VHE was expected to provide indispensable information for modeling by breaking the degeneracy of the model related to the magnetic field strength and the energy of the emitting electrons. This degeneracy cannot be resolved using only the properties of the emission produced via the synchrotron channel, and some additional information about the emission generated through some other radiation channel is required.

At least for a few GRBs, Fermi/LAT detected photons with energy exceeding $100\,\mathrm{GeV}$ [6]. Although these detections help constrain the flux level of the IC component, the information obtained with Fermi/LAT may still be inconclusive. To illustrate the difficulty that appears in this analysis, let us roughly compare the luminosity of the synchrotron, L_{syn}, and Thomson (i.e., non-relativistic regime of IC scattering), L_{T}, components:

$$\frac{L_{\mathrm{syn}}}{L_{\mathrm{T}}} = \frac{w_{\mathrm{b}}}{w_{\mathrm{ph}}}\,. \tag{1}$$

Here w_{b} and w_{ph} are energy densities of magnetic and photon targets, respectively. The strength of the magnetic field in the production region is determined by the operation of magnetic field amplification processes, which are a subject for intense theoretical and numerical analysis now. However, the results of these studies may not yet be conclusive as, for example, the pair-creation process (which typically remains beyond the scope of the study) may have a strong impact on the field amplification process [11]. Thus, a self-consistent treatment of field amplification appears to be currently beyond the scope of theoretic description or numerical simulations. Therefore, one typically introduces a phenomenological parameter, say η_{b}, which defines the magnetic field strength in the production region. The energy density of the target photons, w_{ph}, depends on the fraction of the energy dissipated at the shock, which is transferred to the nonthermal particle distribution, and on the radiative and adiabatic loss ratio. These quantities may again have a complex relation to the microscopic processes that occur in the forward shock; therefore, typically all this complexity is hidden in another phenomenological parameter, in radiation efficiency η. Combining these standard assumptions, we obtain that the flux ratio of the synchrotron and Thomson components is determined by the ratio of two phenomenological quantities

$$\frac{L_{\mathrm{syn}}}{L_{\mathrm{T}}} = \frac{\eta_{\mathrm{b}}}{\eta}\,, \tag{2}$$

which are typically treated as independent model parameters. Therefore, basic SSC models have the potential to reproduce the flux ratio of the synchrotron and IC components in a relatively wide range, without the need to constrain the parameters in a meaningful way or improve the treatment of the physical process. This internal flexibility of SSC models implies that somewhat more detailed information (than just its flux level) about the VHE component generated by GRB afterglow is required to constrain the physical conditions in the production region. Due to the small collection area of space-born instruments, such improved observational can be obtained only with ground-based Cherenkov telescopes.

2. Detection of GRBs in the VHE regime

At the time of writing of this proceedings, several GRBs had been detected in the VHE regime with ground-based Cherenkov detectors. MAGIC collaboration reported on the detection of GRB 160821B [12], GRB 190114C [13], GRB 201015A [14], and GRB 201216C [15]. These events cover a quite diverse set of bursts, with GRB 160821B being one of the most nearby short GRBs (the redshift of the host galaxy is estimated to be $z = 0.16$ [16]); GRB 190114C is an exceptionally powerful burst coming from a relatively small distance of $z = 0.42$ [17]; finally GRB 201216C is associated with a host galaxy located at a record distance of $z = 1.1$ [18].

Three of the four GRBs detected with MAGIC had a relatively weak signal, i.e., the detection significance was at the level of $\lesssim 5\sigma$, providing a little of constraints for modeling. The fourth burst, GRB 190114C, was a very different case. The detected flux of GRB 190114C was exceptionally high, allowing a very clear detection with significance exceeding the level of 50σ [13]. Fortunately, MAGIC was able to start observing this event just 68 s after the trigger, allowing the study of the early afterglow phase in the VHE regime. This GRB was also detected across the entire frequency range, most notably in the X-ray band with *Swift*-XRT and at GeV energies with Fermi/LAT [19]. The comparison of flux levels in the X-ray, GeV, and TeV bands suggests a spectral energy distribution (SED) that shows a two-hump structure, which was interpreted as evidence for the realization of the SSC scenario [20]. This conclusion is based on the observation that the flux level detected in the Fermi/LAT band appears to be somewhat smaller than those seen in the X-ray and TeV bands. However, this could be caused by an unfavorable choice of the binning intervals, and a statistical analysis of photon energies and arrival times in the Fermi/LAT band suggests that the GeV flux is comparable to the one reported in the VHE regime [21]. This makes claims of two-component SED less robust. We note that this conclusion is consistent with studies that combine X-ray and GeV data for this specific GRB [19] and for a number of Fermi/LAT-detected GRBs [22].

H.E.S.S. collaboration reported on the detection of two bursts: GRB 180728B [9] and GRB 190829A [23]. GRB 180728B represents an event similar to GRB 190114C in terms of the burst power and distance: its isotropic energy was estimated to $E_0 = 6 \times 10^{53}$ erg (in the band 50 – 300 keV, see in Ref. [9]) and the redshift of the host galaxy is $z = 0.653$ [24]. However, the observations started significantly later in the afterglow phase compared to the MAGIC observations of GRB 190114C — H.E.S.S. could start observing the burst direction only 10 hours after the trigger. Despite this unfavorable delay, the event was detected with a significance exceeding the level of 5σ. This detection had shown the feasibility of observing GRBs late in the afterglow phase with IACTs, significantly simplifying the detection of these phenomena in the VHE regime.

GRB 190829A represents a low-power explosion with the estimated total isotropic energy of $E_{\rm iso} \approx 2 \times 10^{50}$ erg in the band $10 - 10^3$ keV [25]. However, this relatively low power was compensated for by an exceptionally close proximity of the host galaxy, $z \approx 0.08$ [26]. This allowed detecting the signal from this GRB for a very long period: the observation started 4 hours and the signal was still detected up to 56 hours after the trigger [27]. Thus, the H.E.S.S. collaboration published a lightcurve that contains five data points enabling the study of the time evolution of the VHE emission. The analysis has revealed a remarkable consistency of the VHE and X-ray lightcurves, which have almost identical time decay indexes, $\alpha_{\rm vhe} = 1.09 \pm 0.05$ and $\alpha_{\rm xrt} = 1.07 \pm 0.09$, respectively [27].

The close proximity of the galaxy hosting GRB 190829A also implied a quite modest optical depth for TeV gamma-rays due to their interaction with low-energy photons from the extragalactic background light (EBL). For the EBL model by Ref. [28] the attenuation factor, e^{τ}, for gamma-ray energy $E < 3$ TeV is smaller than 5 allowing one to study the spectrum of GRB 190829A in an unprecedented energy interval, from 0.18 to 3.3 TeV. Study of the spectral properties of the VHE emission had revealed no indication of the curvature of VHE spectrum after the correction for the EBL attenuation. It is important to note that given the proximity of the host galaxy, this conclusion depends very weakly on the adopted model for EBL. Thus, the claim of an intrinsic powerlaw spectrum in the energy interval indicated above can be treated as model-independent (to extent possible in high-energy astrophysics). Furthermore, the slope of the VHE powerlaw spectrum agrees remarkably well with the slope measured in the X-ray energy band, $\gamma_{\rm vhe} = 2.07 \pm 0.09$ (for the combined dataset that includes all three observation nights) and $\gamma_{\rm xrt} = 2.03 \pm 0.06$ (for the first night; for details see Ref. [27]).

Finally, the LHAASO collaboration reported on the detection of GRB 221009A [29]. Thanks to the relative proximity of this burst, $z = 0.151$, and its exceptionally high isotropic energy of $E_0 = 2 \times 10^{54}$ erg (which make it one of the most powerful GRBs ever detected), it has been detected across the entire electromagnetic spectrum. The wide field of view and nearly 100% duty cycle of LHAASO provided the perfect condition for observing this bright GRB, provided that it was visible to LHAASO at the trigger time. Although at the time of this writing, the key results from these observations remained unpublished, several key findings were reported in the announcement. In the first place, we expect that the VHE emission from the prompt phase has been detected or LHAASO could provide some meaningful upper limits on that component. The significant number of photons detected in the VHE regime (with more than 5,000 reported in the detection circular [29]) implies that LHAASO obtained a very detailed lightcurve that covers the prompt phase and the afterglow at least for several first hours after the trigger. For the reported host galaxy redshift of $z = 0.151$ the attenuation due to interactions with EBL of TeV gamma-rays should be very significant: the optical depth for $E = 1$ TeV is close to $\tau \approx 1$ and it rapidly increases for higher photon energies [30]. For example, for $E = 20$ TeV the depth is already very significant $\tau \approx 10$ (see in Fig. 13 of Ref. [30]). Despite the significant expected attenuation for multi-TeV photons, LHAASO reported detecting photons with an energy up to $E = 18$ TeV [29]. At the moment of writing, it is not clear if the broadband spectrum measured with LHAASO favors some nonstandard physics, such as photon-axion oscillation or Lorentz invariance violation (see, e.g., in Ref. [31]), or can still be explained with less extravagant models. Once the analysis of this exciting dataset is over, the obtained spectrum and light curve should provide indispensable information for modeling and testing of different scenarios.

3. Summary

The long-awaited detection of GRBs in the VHE regime has brought new observational insights and challenged conventional models for these sources. The initial detection of GRB 190114C and

GRB 180728B in the VHE regime was considered by many as a strong confirmation of the SSC paradigm [20]. However, already this detection revealed some features that were not in perfect agreement with the expectations from the SSC models. For example, the powerlaw index of the intrinsic spectrum of GRB 190114C was obtained to be $\gamma_{\rm vhe} = 2.22^{+0.23}_{-0.25}$, with no evidence of a spectral break or cutoff. Similarly, the H.E.S.S. observations of GRB 180728B favored a hard photon index of $\gamma_{\rm vhe} = 1.6 \pm 1.2$ [9], although the observational uncertainties in this case are very significant. In general, SSC models predict IC components that are not consistent with a broad powerlaw spectrum. The VHE spectrum GRB 190114C was measured in a relatively narrow range of energies; therefore, different SSCs can still reproduce this spectrum [32]. However, the tension between the predictions of the SSC models and the observational data became very clear when the H.E.S.S. collaboration presented their measurement of the VHE spectrum of GRB 190829A [33]. This time, the spectrum was measured in a broader energy interval, and again there was no evidence of a spectral break or cutoff [27]. In the near future, the LHAASO collaboration will present the VHE spectrum and lightcurve of GRB 221009A, which will bring further challenges and potentially can significantly improve our understanding of GRB.

Acknowledgments

DK acknowledges support by the RSF grant No. 21-12-00416.

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