The Detection of Very High Energy Photons in Gamma Ray Bursts

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Abstract

Gamma Ray Bursts (GRBs) are energetic cosmic explosions in the universe with a short-lived burst phase emitting in the gamma-ray bands and a long-lived afterglow phase emitting from optical to radio bands of the electromagnetic spectrum. Recent observations with Cherenkov detectors have identified Very High Energy (VHE) photons in GRBs typically of Teraelectron Volt (TeV) energy range. In this article, the properties of VHE detected GRBs are summarised. The multi-wavelength afterglow evolution of two VHE GRBs (19014C and 190829A) is discussed and a comparison of their properties in the context of GRB afterglow population is discussed.

Introduction

GRBs are the most energetic cosmic explosions in the universe that emit more energy in a few seconds than the Sun would emit in its entire lifetime. GRBs were serendipitously discovered by the US Vela nuclear test detection satellites in 1967. GRBs are basically brief, ephemeral flashes of γ-ray photons that can last from a few milliseconds to thousands of seconds. Traditionally they are classified as long and short bursts depending on the T_{90} value [1] where T_{90} is the time duration in which 90% photons are accumulated by the detector. GRBs are isotropically distributed in the sky indicating their cosmological origin. With improved observational facilities, GRBs have been located upto a photometric redshift of 9.4 [2] which makes them potential candidates to study the early universe and population-III stars. These energetic events occur either due to the collapse of massive stars (M> $8M_{\odot}$) or the merger of binary compact objects [3, 4].

GRBs dissipate around 10^{48} to 10^{54} erg of energy in the form of a jet. The jet produces shock waves when the shells inside the jet interact with each other, which produce the γ-ray photons. As the blastwave from the explosion sweeps up the external medium, local random magnetic fields accelerate electrons to ultra-relativistic velocities, these eventually generate a long lasting afterglow from radio to X-ray frequencies, predominantly via synchrotron radiation. Afterglow studies are an invaluable tool to answer fundamental

Table 1: *Properties of the TeV detected GRBs.*

GRB	redshift (z)	T_{90} (s)	$E_{\rm iso}$ (erg)	Maximum photon energy (TeV)	TeV detection facility	References
GRB 180720B	0.654	51.1 ± 3.0	$6.82^{+0.24}_{-0.22} \times 10^{53}$	0.44	H.E.S.S.	[5, 6]
GRB 190114C	0.425	~ 116	$3.5 \pm 0.1 \times 10^{53}$	1	MAGIC	[7]
GRB 190829A	0.078	57 ± 3	$\sim 2.0 \times 10^{50}$	3.3	H.E.S.S.	[8]
GRB 201015A	0.426	9.78 ± 3.47	$\sim 3.86 \times 10^{51}$	-	MAGIC	[9]
GRB 201216C	1.1	29.95 ± 0.57	$\sim 6.32 \times 10^{53}$	-	MAGIC	[10]
GRB 221009A†	0.151	1068.40 ± 13.38	$\sim 1.2 \times 10^{55}$	251	Carpet-2	[11]

† Also detected by MAGIC

questions on radiation processes in extreme environments. Various parameters associated with the jet and its surroundings can be constrained using high-cadence multi-wavelength data and afterglow modeling.

Until a few years back, the afterglow emission was known in optical/IR, radio/mm and X-ray bands. But the availability of sensitive Cherenkov detectors in the last few years, has unearthed the VHE emission in GRBs. In this article, we discuss the properties of VHE GRBs and compare their evolution to the known GRB population. In particular, we will focus on two GRBs 190114C and 190829A.

Detection of GRBs at TeV energies

In recent years, a breakthrough came with the detection of VHE photons from GRBs. This radiation was observed with the Cherenkov detectors which can detect photons with energies ~ 100 TeV. The emission mechanism giving rise to VHE photons in GRBs is still debatable. In the afterglow scenario, the standard synchrotron radiation cannot explain the VHE photons as the shock has already decelerated by then. The plausability of other emission mechanisms such as Synchrotron Self-Compton (SSC), proton synchrotron, and hadronic processes could be used to explain the sub-TeV photons. These scenarios can be investigated with detailed modeling of the increasing number of VHE detected GRBs. Thus, detection of VHE emission provide invaluable insights into the new radiation mechanism associated with GRBs.

On 20 July, 2018 the High Energy Stereoscopic System (H.E.S.S.) recorded the very first TeV photons from GRB 180720B. GRB 190114C is the second GRB in this list for which TeV photons were detected using the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) air Cherenkov telescope on 14 January, 2019. This is one of the highest energetic GRB ever detected by the *Fermi* space mission. In the same year, H.E.S.S. recorded the TeV photons from a low luminosity GRB 190829A. In the year 2020, MAGIC detected high energy radiation from two GRBs 201015A and 201216C. Recently, the Large High Altitude Air Shower Observatory (LHAASO) and CARPET–2 Cherenkov detectors detected VHE photons from the brightest GRB ever detected, GRB 221009A, which came to be popularly known as the *Burst Of All Times (BOAT)*. So far VHE emission has been reported in six GRBs. The redshift, T_{90}, isotropic equivalent energy (E_{iso}), the maximum energy of the TeV photon detected and the facility which detected the TeV photons are listed in Table 1.

GRB 190114C: the second TeV detected GRB

GRB 190114C was first detected by the Burst Alert Telescope (BAT) onboard *the Neil Gehrels Swift Observatory* (hereafter *Swift*) on 14 January, 2019 and a multi-wavelength follow-up was triggered. Several other space-based high-energy missions such as *INTEGRAL*, *Insight*, *Konus-Wind* and *Fermi* satellites also localised this GRB. *Fermi* promptly detected a 22.9 GeV photon 15 s after the burst trigger. A historically rapid follow-up observation, ~ 50 s after the BAT trigger of GRB 190114C, was performed by the twin MAGIC telescopes. The MAGIC real-time analysis detected very high-energy emission >300 GeV with a significance of more than 20σ in the first 20 min of observations. However, after the initial flash of VHE gamma-ray photons, the VHE emission quickly faded, as expected for a GRB and validating the connection between the VHE flash with the GRB [7].

Furthermore, the X-ray and UV/optical afterglows were localised by the *Swift* X-ray Telescope (XRT) and UV/Optical Telescope (UVOT) within tens of seconds after the burst trigger. Following the precise localisation and detection of the longer wavelength afterglow, we conducted an extensive observing campaign with the Australia Telescope Compact Array (ATCA), Atacama Large Millimetre/submillimetre Array (ALMA), and Giant Metrewave Radio Telescope (GMRT) at radio frequencies and with the 0.7 m GROWTH- India telescope (GIT), the 1.3 m Devasthal Fast Optical Telescope (DFOT), and the 2.0 m Himalayan Chandra Telescope (HCT) in the optical bands to study the multiband evolution of the afterglow. The multiband light curves of the afterglow of GRB 190114C from X-ray to radio/mm bands display a complex behaviour. The X-ray light curve follows a temporal decay index of $\alpha_X = 1.344 \pm 0.003$ from 68 s to ~ 10 d, and shows hint of a steeper decline thereafter. The ATCA 9 and 5.5 GHz data offer a temporal coverage of two orders of magnitude in days and both these light curves follow a temporal decay index of ~1 at late times whereas the

97 GHz light curve falls slowly with an index of 0.71 ± 0.02. The optical R bands follows a 0.85 ± 0.06 decay. The empirical fits performed on a selected set of multiband light curves are shown in Figure 1 [12].

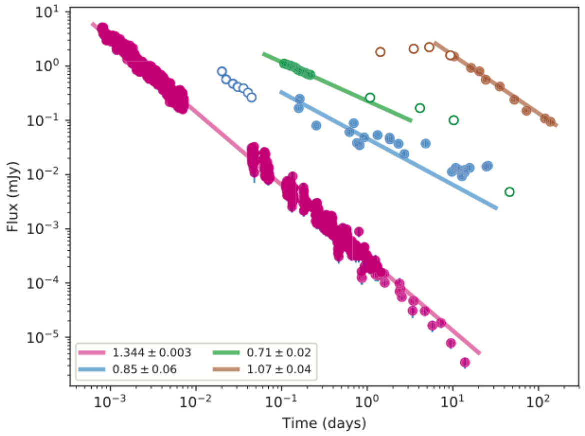

Figure 1: *Multiband light curves and empirical fits ($F_\nu \propto t^{-\alpha}$) to the afterglow of GRB 190114C from X-ray to the radio/mm bands. X-ray (violet), R band (blue), 97 GHz (green), and 9 GHz (brown). The open symbols represent the data excluded from the fit. [12]*

GRB 190829A: the closest TeV detected GRB

On 29 August, 2019 the *Swift*, *Fermi* and *Konus-Wind* missions triggered on a peculiar GRB 190829A. The burst phase light curve in gamma-rays exhibited a double episodic structure. *Swift* XRT promptly localised the X-ray afterglow of the burst. Several ground based optical observatories detected the optical afterglow and followed its evolution. The energetic TeV photons were detected by H.E.S.S. on three consecutive nights (between 4.3 and 55.9 hours since the trigger) [8]. GRB 190829A is the lowest luminosity GRB and one of the closest bursts for which TeV photons are detected. We carried out an exhaustive campaign observing in radio/mm bands with the GMRT and ALMA to probe the transition from an optically thick to a thin regime. Despite being a low-luminosity GRB, it was bright in radio bands, and was observed up to ~ 300 days since the explosion. The mm and radio light curves of the afterglow of GRB 190829A are shown in Figure 2.

Afterglow properties of GRB 190114C and GRB 190829A in the context of other GRBs

In Figure 3, a comparison of the flux densities of two TeV-detected GRBs (190114C and 190829A) in mm and radio bands with a sample of GRBs plotted as a function of redshift is performed. Because of their low redshifts, the mm and radio afterglows of these two GRB are brighter. But these bursts are average or low-luminosity events in comparison to a larger sample.

Figure 4 shows the corrected R-band light curves of TeV detected GRBs in comparison to the other GRB afterglow sample. The afterglow light curves are shifted to the z = 1

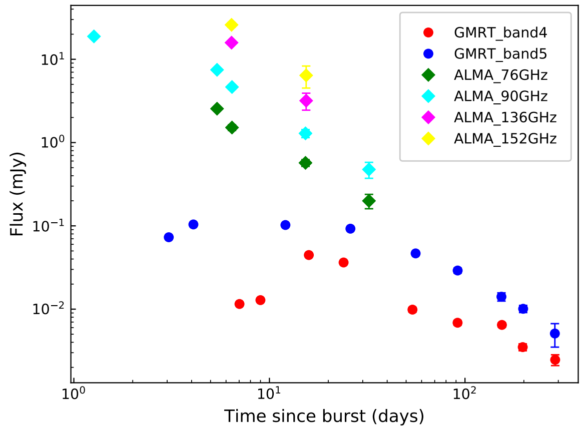

Figure 2: *Multi-band afterglow light curves of GRB 190829A in cm/mm bands.*

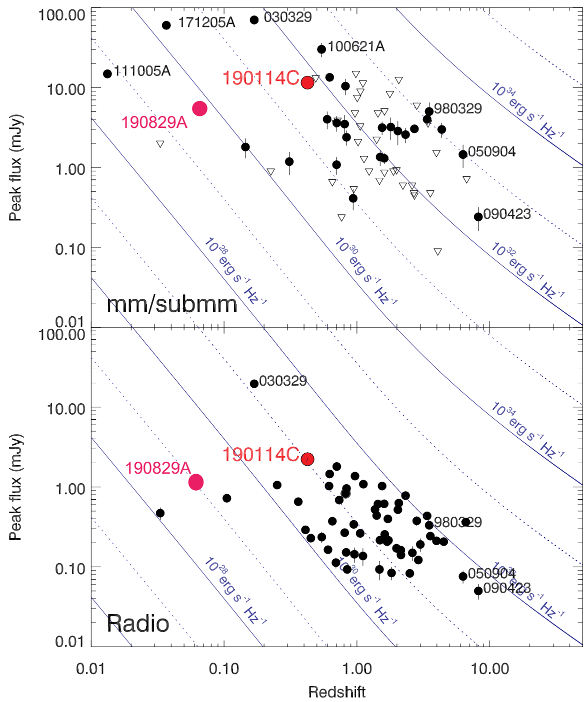

Figure 3: *Comparison of peak flux densities in mm and cm bands of GRB 190114C and GRB 190829A with a sample of GRBs plotted as a function of redshift. Both solid and dotted blue lines indicate equal luminosity with the most luminous GRB at the top right corner. A few important GRBs are featured in this figure. [12]*

frame and corrected for the host galaxy extinction following the prescription given by [13]. The afterglow of GRB 190114C suffers a large extinction but it resembles average nature of RGBs at early times. It becomes one of the most luminous afterglows later on emanating from the slow decay which is uncommon for GRBs after a few days since burst. The afterglow of GRB 190829A, despite the correction for the large line-of-sight extinction, is found to be underluminous than other GRBs in the sample, making it inevitably similar to the low-luminosity GRBs in the local Universe. Whereas the afterglow of GRB 180720B is seen to be similar to that of GRB 190114C, especially at early times but an average aferglow in the context of the larger GRB sample. GRB 180729B does not exhibit any significant dust which is in contrast to the other two TeV detected GRBs 190114C and 190829A where evidence of large line-of-sight extinction was found.

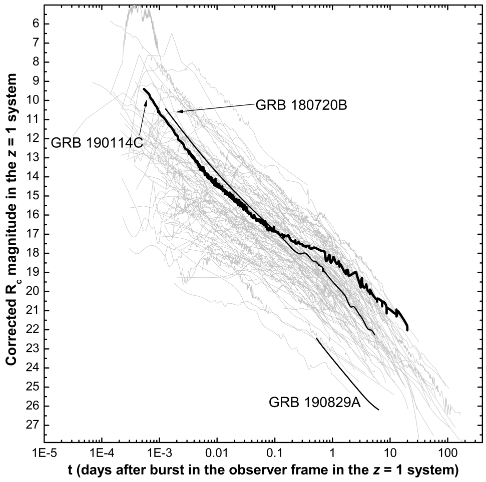

Figure 4: *The optical R-band light curve of the afterglow of GRBs 190114C and 190829A in comparison to a large afterglow sample. [12]*

A thorough comparison of the afterglow light curves thus signals that the detected VHE emission is neither linked inextricably to the extinction along the line-of-sight, nor to the luminosity of the afterglow.

Summary

In this article, a summary of the recent VHE detections of the GRBs is presented. So far, six GRBs with VHE emission have been detected by the MAGIC, H. E. S. S. and CARPET-2 detectors. We focus on the afterglows of two GRBs 190114C and 190829A for which we ran extensive observing campaigns in long wavelengths to track their evolution. A thorough comparison of their afterglows in radio, mm and optical bands does not suggest any peculiarity that can be linked with the detected VHE emission. Nonetheless the VHE emission seen in GRBs is very interesting and opens an unexplored windows to understand the radiation mechanism associated with GRBs.

Acknowledgements

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