PROCEEDINGS OF SCIENCE

Observing optical and high energy emissions from GRBs

Tania Garrigoux[*]
Centre for Space Research, North-West University, Potchefstroom 2520, South Africa
E-mail: `taniagv@gmail.com`

Gamma-ray bursts (GRBs) are some of the most powerful and exotic events in the universe. Due to their high luminosity, they are visible to high redshifts providing excellent probes of the distant universe. Although their emissions are detected across the electromagnetic spectrum, their behavior at the highest energies ($>$ 100 GeV) is unknown. The detection of these very high energy (VHE) photons is of importance, as it would help understand their emission mechanism and could provide evidence of Ultra-High-Energy Cosmic Rays (UHECR) acceleration in GRB jets. Hence, it is among the primary science goals of H.E.S.S.-II, the second phase of the H.E.S.S. experiment. Optical data plays an important role in constraining theoretical models for GRBs, especially when analyzed together with future VHE and available gamma-ray, X-ray and ultraviolet data. Thus, simultaneous follow-up observations by both H.E.S.S.-II and optical telescopes such as SALT, of GRBs detected at lower energies by Fermi-LAT or Swift-BAT, would be most profitable. In addition, optical data provides crucial information on redshift and host galaxies. The H.E.S.S. telescopes will most probably detect low redshift GRBs, due to the Extragalactic Background Light (EBL) gamma-gamma absorption. As a consequence, rapid follow-up observations for redshift measurements (within a few hours) of GRBs will be needed to decide whether H.E.S.S. should follow up as well. Furthermore, as the distance sets the overall energy/luminosity scale, the determination of the redshift is necessary for a meaningful theoretical interpretation.

SALT Science Conference 2015 -SSC2015-
1-5 June, 2015
Stellenbosch Institute of Advanced Study, South Africa

---

[*] Speaker.

PoS(SSC2015)024

1. Introduction

The last decade has seen the emergence of a new branch of astrophysics at extreme energies, particularly the TeV gamma-ray band. Very high energy gamma-ray astrophysics studies the most energetic phenomena in the universe, among which are Gamma-ray Bursts (GRBs), short flashes of gamma rays with a peak in the MeV band. GRBs are the most luminous ($L \sim 10^{51}$ erg/s) after the Big Bang and violent (energy output $E \sim 10^{54}$ erg) explosions in the universe. They were discovered in 1967 but their research has made rapid progress these last two decades, boosted by results from satellite instruments, the most recent being the Large Area Telescope (LAT) and Gamma-ray Burst Monitor (GBM) onboard the Fermi Gamma-ray Space Telescope. Not much about them is known or understood, hence being one of the most enigmatic phenomena in the universe. Since no known process can yield so much energy in such short timescales, most of the energy is believed to be concentrated in a relativistic jet. (For recent reviews, see [1, 2, 3])

2. GRBs key-science topics

GRBs are of potential great importance for various fields of physics and astrophysics. From model-independent considerations, they are leading candidate sources among the few that remain for Ultra-High-Energy Cosmic Rays (UHECRs), despite the fact that it is complicated to determine a definite connection with the arrival direction of UHECRs. Although these are the highest energy particles (up to $\sim 10^{20}$ eV) known to exist, their origin continues to be a mystery. Moreover, the hadronic processes involved in their production may implicate observable fluxes of high-energy neutrinos. These could be detected via hadronic gamma-ray signatures and/or in association with current and future neutrino telescopes, such as IceCube and KM3NeT.

Among the particularities of GRBs is their flux variability. It can be seen in the MeV and GeV energy bands and happens over short timescales ($\sim$0.01–1000 s). The high-quality measurement of time-resolved spectra and energy-dependent variability in the GeV band is a unique probe for fundamental physics. For example, because gamma-rays with very short wavelengths become sensitive to the microstructure of space-time, at these very high energies special relativity and other "exotic" phenomena can be checked and/or constrained, such as Lorentz Invariance Violation (LIV) or quantum gravity models. Thus GRBs are valuable beacons for this kind of precision tests.

GRBs can be of significant interest for observational cosmology. GRBs occur at cosmological distances, opening a window to the era of cosmic reionization and the earliest star formation. One recently detected GRB ($z \sim 9.4$) represents the most ancient known astrophysical source. Furthermore, during their propagation in the galaxy, gamma-rays can interact with photons at lower energies, converting into electron-positron pairs, with a cross-section depending on the energy of both particles. At 1 TeV, the gamma-rays will be more likely to interact and be affected by infrared photons. It so happens that the universe is populated by the Extragalactic Background Light (EBL), the diffuse and nearly isotropic background of infrared-optical-ultraviolet radiation from outside our Galaxy accumulated mainly from star formation and AGN since the epoch of reionization. Hence, at high energies, the absorption of gamma-rays due to these photons will drastically reduce the observed flux, leading to an indirect measurement of the EBL. A detailed study of the EBL as a function of energy and redshift could yield insight into the cosmic history of star and galaxy formation in the universe, as the EBL holds fundamental information about these processes. It is a critical observable for models of reionization, galaxy formation and evolution, as well as high-energy-astrophysics phenomena. EBL indirect measurements have been obtained by analysing spectral features of AGN at very high energies [4]. Because of the extremely high redshifts at which they can be observed, GRBs spectra would constitute an important addition for the EBL analysis.

Because of their strategic importance in the comprehension of our universe, GRBs have been key science research subjects in astrophysics over the last couple of decades. Nonetheless, many of their basic aspects are still unknown or unclear. For instance, the formation and characteristics (outflow speed, emission site, etc) of the relativistic jet along with the physical mechanisms of particle acceleration and energy dissipation that leads to the observed emission are poorly understood. The central engine's identity or nature has not been confirmed yet, although at least some long GRBs (>2 s) have been associated with the explosion of massive stars resulting in a supernova from core collapse. Short GRBs (<2 s) on the other hand, are believed to originate from binary neutron star or neutron star-black hole mergers.

3. The importance of multi-wavelength observations

GRBs are characterized by a prompt MeV-band emission accompanied by afterglows that span the spectrum from radio to X-rays, decaying gradually over hours to days or more. Multi-wavelength coverage will be a powerful tool for exploring the violent mechanisms at work at the base of GRBs prompt and afterglow emissions. Our understanding of the jet physics, including their formation and collimation as well as the propagation of particles and the development of shocks and turbulence inside, might drastically improve. The comprehension of how charged particles are accelerated in jet plasmas through shocks and/or turbulence and/or magnetic reconnection would have repercussions on the possible finding of a connection with ultra high-energy cosmic rays [5, 6]. Multi-frequency coverage of the afterglow evolution over a collection of timescales is essential for a decisive diagnosis in this respect.

The origin of the emissions, in particular the ones in the GeV and MeV band, is widely unknown. During the prompt phase of the MeV emission, the GeV emission has been seen to vary significantly, hence interpreting it as the high-energy counterpart of the prompt emission from the same emitting region. The long-lived, smooth decay phase, on the other hand, is attributed to the afterglow. Again, good multi-frequency coverage of the afterglow from early times would be crucial to unravel its origin. Temporally extended GeV gamma-ray emission has been shown to correlate with X-ray and optical afterglow data [7, 8]. This type of simultaneous multi-wavelength observations of GRBs have significant implications in GRB modeling and are needed in the estimation of their energy content, velocity and emission mechanism (see for instance [9] and [10]). Furthermore, chances are higher for observing GRBs in coincidence with X-ray flares that present strong and rapid variability. For this reason, they are normally thought to reflect the long-lasting activity of the central engine. However, they could also be attributed to sporadic late-time magnetic reconnection events within a highly magnetized jet. It is necessary to study the high-energy properties of X-ray flares and compare them with the prompt emission, in order to reveal their true provenance.

3.1 High energy observations

In a general way, phenomena that induce very high energy emissions are the source of other secondary events seen at longer wavelengths, that can be explained with the very high energy primary data. To study the high-energy photons coming from GRBs within the multi-frequency context would allow us to delineate light curves and spectra over the GeV band, which is essential to define the precise emission site of the high-energy gamma-rays. The latest observations of Fermi have revealed intense radiation in the GeV band from a respectable number of GRBs. In general, this emission lasts longer than the one in the MeV band and may release a considerable fraction of its energy. Even though the GeV emission can be interpreted in many ways and the afterglow has been explained in some cases, its origin remains elusive. Robust estimates of the total energy radiated in the GeV band can help put constraints on the central engine.

The low energy emission (radio to X-ray afterglow emission) is believed to be dominated by the synchrotron radiation from a relativistic electron population. However, at higher energies, the radiation mechanism remains very uncertain. Depending on the matter composition, two types of models are discussed. In the leptonic model, the emitted relativistic particles are considered to be essentially electrons and positrons whereas in the hadronic model it would consist of protons and electrons. Yet, these are poorly constrained, for both models could describe the prompt emission. Nevertheless, the results in both cases are never entirely satisfactory for there are always some properties (light curve features, thermal vs non-thermal contributions, etc) that they fail to explain. In addition to simultaneous snap shots of the spectra, variability also plays a key role in constraining radiation models, for it would allow us to discriminate between the leptonic and hadronic mechanisms. Indeed, the acceleration and cooling time scales for protons and nuclei that could be detected in the GeV–TeV band are usually much longer than for leptons.

3.2 Optical observations

Three phases [11] have been observed in the optical emissions of GRBs. During the prompt period, an optical emission has been observed varying along with the gamma-rays [12]. In addition, the afterglow can be divided into two stages: an early optical emission lasting for tens of minutes after the extinction of the prompt gamma emission [13] and a late one, which can persist for hours or even days [14].

Optical observations are required to obtain light curves and spectra. When used with simultaneous muti-wavelength data to reconstruct the spectral energy distributions, they help constrain theoretical models and thus understand the general mechanisms at work in GRBs. They are also needed to characterize breaks in the afterglow light curves, which are linked to the Lorentz factor and opening angle of the GRBs' jetted outflows. Moreover, optical data can provide essential information on the host galaxies, which are crucial in cosmic GRBs rate studies.

Optical observations hold additional special significance. Indeed, by using spectroscopy, the redshift of the GRBs can in some cases be determined. Redshifts are not only valuable for a meaningful theoretical interpretation, but are also used to decide whether a very high energy ground based experiment should follow up on a GRB alert or not, as will be explained in the next section.

4. Observing GRBs with H.E.S.S.

GRBs have not yet been detected at very high energies (> 100 GeV). The H.E.S.S. experiment, the only current ground based Čerenkov telescope array in the Southern Hemisphere, has made GRB detection one of its key priorities, especially since the addition of its fifth and largest telescope. For more details on GRB observations with H.E.S.S., see [15].

4.1 The H.E.S.S. experiment

Since fall 2003, the High Energy Stereoscopic System (H.E.S.S.) [16] has been devoted to the observations of very high energy gamma rays, in the 100 GeV to a few tens of TeV energy range for the first phase and with a lower energy threshold, of about 20 GeV, for the second phase starting in July 2012. It enables scientists to explore gamma-ray sources with intensities at a level of a few thousandths of the flux of the Crab nebula (the brightest "steady" source of gamma rays in the sky mainly observable in the northern hemisphere). Its primary goal is to provide the experimental basis for an improved understanding of the acceleration, propagation and interactions of non-thermal populations of particles. The instrument consists of an array of five Imaging Atmospheric Čerenkov Telescopes (IACTs) situated in the Khomas Highland of Namibia, an area well known for its excellent optical quality. This southern location provides optimal conditions for observing the center of our Galaxy, a region full of high-energy sources as supernova remnants and pulsars, which are of significant interest for gamma-ray astronomy.

As the name suggests, the IACT detection technique uses the Čerenkov effect. Gamma photons interacting with the atmosphere produce a shower of secondary particles that propagate at a speed faster than light in the medium, emitting the blue light characteristic of the Čerenkov radiation, which is what the telescopes detect. The initial particle is determined thanks to the selection criteria on the shape of the image in the camera, typically an elliptical trace for a gamma photon. The reconstruction of the geometry of the shower is possible using stereoscopy. With it, information on the primary particle (energy, direction, etc) is deduced.

With a single telescope providing a single view of a shower, it is difficult to reconstruct the exact geometry of the air shower in space. To accomplish this, multiple telescopes are used which view the shower from different points and allow a stereoscopic reconstruction of the shower geometry. The four telescopes corresponding to the phase I of the experiment (named CT1, CT2, CT3 and CT4) are 12 m in diameter, weighing around 60 tons, and are arranged in the form of a square 120 m on a side. This spacing is a compromise between the large base needed to provide views from each telescope different enough as to allow a good stereoscopic reconstruction, and the requirement that two or more telescopes detect the shower, for the Čerenkov light pool is usually around 250 m in diameter.

4.2 H.E.S.S. II

While the first H.E.S.S. telescope began operation in Summer 2002, with the whole phase one array observing by December 2003, the fifth telescope (called CT5) was added at the center of this array for the second phase of the project (H.E.S.S. II) in 2012. The aim is not only to lower the energy threshold as already mentioned, but also to increase the sensitivity and angular resolution of the instrument, with more telescopes observing at the same time. With its 28 m diameter, about

600 m^2 collection area as compared to ∼108 m^2 for a phase 1 telescope, and 580 tons weight, CT5 is the largest IACT ever built on Earth. The simultaneous use of these two different types of telescopes, CT1-4 and CT5, H.E.S.S. II constitutes the first hybrid IACT array, and paves the way for future projects like the Čerenkov Telescope Array (CTA).

At 30 GeV, H.E.S.S. II has a detection area almost 10 times larger than the Fermi-LAT, while maintaining an angular resolution of around 0.25°. Nonetheless, the drive system was updated over that of the original system [17], for a rapid repointing: CT5 rotation speed is twice that of phase I telescopes, with a full rotation possible in 3.5 minutes. An additional feature is its ability to slew through zenith instead of turning, called *reverse-mode* pointing. Furthermore, CT5 has a dedicated target of opportunity (ToO) observation system. The goal is to reduce the number of hardware and software transitions required before the observations [18]. The system is tested with fake alerts to be constantly improved. This minimises the repointing time of the telescope.

The H.E.S.S. experiment is part of the Gamma-ray Coordinates Network (GCN), which distributes details of GRB detections with other instruments as quickly as possible. H.E.S.S. follows up on GRB alerts from two instruments: the Swift-BAT [19] and Fermi-GBM [20]. Considering the delay of the alert given by the GCN, the hardware and software transitions as well as the repointing time of the telescopes, the total time before GRB observations can begin after a GCN alert is expected to be less than 2 minutes, for the majority of possible observation positions

There are different selection criteria to determine whether H.E.S.S. should follow up on a GRB alert. Prompt observations are defined as those observable during H.E.S.S. darktime or 1 hour prior to it. The GRB will be observed if its zenith angle stays below 60° for at least 30 mins. 4-6 of these are expected per year. All GRB alerts that do not meet the previous criteria are classified as afterglows. This type of observations are expected to occur 8-12 times per year. The follow-up will only take place if the zenith angle stays below 45° for at least 30 mins. In addition, further cuts are included, based on the delay between burst time and observation time and dependent on redshift. The reason for this comes from the gamma-gamma attenuation explained in Section 2, which results in a gamma-ray horizon of redshift z∼1 at 1 TeV. As a consequence, GRBs with high redshift cannot be detected with this type of instrument and the limited observation time should not be wasted on them. Hence, a quick estimation of the redshift is of great value.

5. Conclusion

GRBs are the most luminous and violent explosions in the universe and have been observed for about 50 years, in radio to high energy gamma-rays. Although they are interesting in many fields (central engine physics, propagation models, exotic physics, etc) and may play a crucial role in the understanding of several major unsolved problems in modern-day astrophysics, many unsolved questions persist. More thorough studies of the spectral shape and variability of these particle populations will help to make progress in the understanding of the jet formation and composition, the processes behind the accelerated particles, and the microphysics of the radiation mechanisms. It is a possibility that this might finally lead to the discovery of the origin of cosmic rays, giving once and for all an answer to this open puzzle. Likewise, light might be shed on other fundamental issues such as the cosmological galaxy evolution and structure formation through a better EBL determination or even the microstructure of space-time at the smallest scales when testing the behavior of highly energetic photons.

As previously expressed, simultaneous multiwavelength observations of GRBs providing high quality light curves and broadband spectra are of significant importance. First, these are needed to determine the radiation mechanisms of prompt GRBs with their early afterglows. Besides, the hadronic emission models explore scenarios that could provide a direct link between the observed gamma-ray emission and the emission of neutrinos and ultra high-energy cosmic rays. In consequence, an additional aim is the search for hadronic signatures associated with the production of UHECR and neutrinos. If the physics of basic radiation models are well constrained, the properties of the whole particle distribution can be characterized from its emission at very high energies. This would be essential for recognizing the acceleration mechanisms at work, another objective of GRBs studies.

The H.E.S.S. experiment, with its rapid repointing system and good low energy performance, is an ideal partner for GRBs follow up observations. It provides a strong chance of GRB detection at very high energies. Furthemore, collaboration with optical intruments is of special benefit, not only to improve the understanding of the physics involved in GRBs, but also for the observation strategy of the H.E.S.S. array.

References

[1] Inoue, S et al. [CTA consortium]. Gamma-ray burst science in the era of the Cherenkov Telescope Array. Astroparticle Physics, Volume 43 (2013) 252-275

[2] Meszaros, P. Gamma ray bursts. Astroparticle Physics, Volume 43 (2013) 134-141

[3] N. Gehrels and S. Razzaque. Gamma-ray bursts in the swift-Fermi era. Frontiers of Physics, Volume 8, 6 (2013) 661-678

[4] A. Abramowski et al. [H.E.S.S. Collaboration] Measurement of the extragalactic background light imprint on the spectra of the brightest blazars observed with H.E.S.S. A&A, 550 (2013) A4

[5] Waxman, E. Gamma-ray bursts: Potential sources of ultra high energy cosmic-rays. Nuclear Physics B Proceedings Supplements, v. 151, iss. 1 [SPECIAL ISSUE] (2006) 46-53

[6] Halzen, F. Pionic photons and neutrinos from cosmic ray accelerators. Astroparticle Physics, Volume 43 (2013) 155-162

[7] Ackermann, M. et al. [Fermi Collaboration]. Multiwavelength Observations of GRB 110731A: GeV Emission from Onset to Afterglow. The Astrophysical Journal, Volume 763, Issue 2, article id. 71 (2013) 19

[8] Ackermann, M. et al. [Fermi Collaboration]. The First Fermi-LAT Gamma-Ray Burst Catalog. The Astrophysical Journal Supplement, Volume 209, Issue 1, article id. 11 (2013) 90

[9] Curran, P. A. et al. Testing the blast wave model with Swift GRBs. Monthly Notices of the Royal Astronomical Society, Volume 395, Issue 1 (2009) 580-592.

[10] Beniamini, P. et al. Energies of GRB blast waves and prompt efficiencies as implied by modelling of X-ray and GeV afterglows. Monthly Notices of the Royal Astronomical Society, Volume 454, Issue 1 (2015) 1073-1085

[11] W.T. Vestrand et al. A link between prompt optical and prompt gamma-ray emission in gamma-ray bursts. Nature 435 (2005) 7039

[12] W.T. Vestrand et al. Energy input and response from prompt and early optical afterglow emission in gamma-ray bursts. Nature 442 (2006) 7099

[13] C. Akerlof et al. Observation of contemporaneous optical radiation from a big gamma-ray burst. Nature 398 (1999) 400-402

[14] D.W. Fox et al. Discovery of Early Optical Emission from GRBs 021211. The Astrophysical Journal Letters 586 (2003) Number 1, L5

[15] D. Parsons et al. The H.E.S.S. II GRB Program. Proceedings of the 34rd International Cosmic Ray Conference (2015)

[16] J.A. Hinton [H.E.S.S. Collaboration]. The Status of the H.E.S.S. Project. New Astron.Rev. 48 (2004) 331-337

[17] P. Hofverberg, R. Kankanyan, M. Panter et al. Commissioning and initial performance of the H.E.S.S. II drive system. Proceedings of the 33rd International Cosmic Ray Conference (2013)

[18] A. Balzer, M. Fussling, P. Hofverberg et al. The Performance of the H.E.S.S. Target of Opportunity Alert System. Proceedings of CHEP (2015)

[19] S. D. Barthelmy, L. M. Barbier, J. R. Cummings et al. The Burst Alert Telescope (BAT) on the SWIFT Midex Mission. Space Science Reviews 120 (2005) 143-164

[20] C. Meegan, G. Lichti, P. N. Bhat, et al. The Fermi Gamma-Ray Burst Monitor. The Astrophysical Journal, Volume 702, 1 (2009) 791-804