Modeling of TeV emission from gamma-ray bursts

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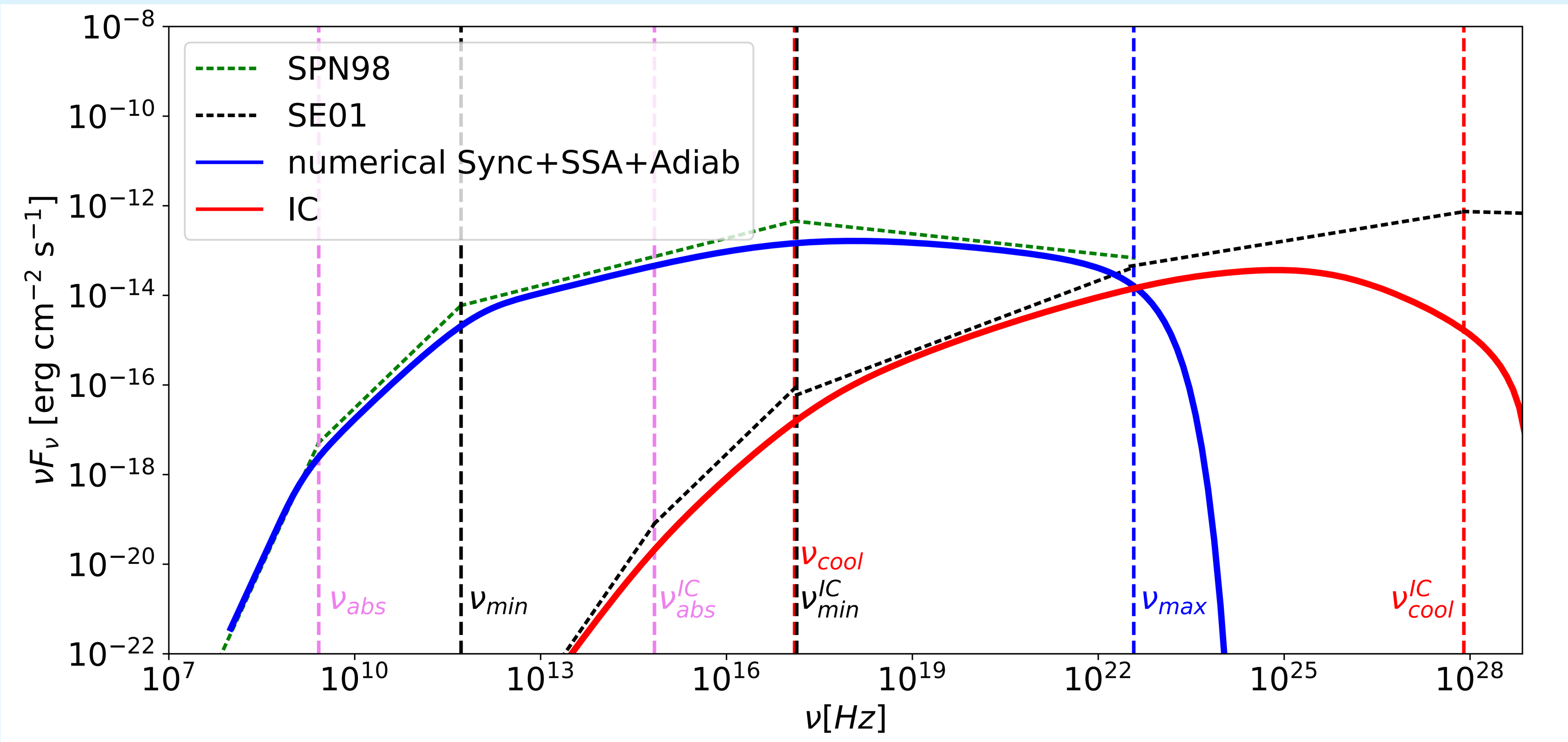
Abstract

The presence of a very high energy (VHE, E > 100 GeV) emission component in gamma-ray bursts has always been one of the most debated open questions both from the observational and the theoretical side. The recent discoveries claimed by the MAGIC and H.E.S.S. telescopes have firmly proved the existence of such component up to TeV energies. These results have been fundamental to directly investigate for the first time the responsible mechanisms and the physical properties of such energetic component as well as its connection with the emission at lower energy bands. The multi-wavelength afterglow emission from the long gamma-ray burst GRB 190114C was successfully explained with a numerical modeling reproducing both the synchrotron and Synchrotron-Self Compton (SSC) radiation emitted from electrons within the external forward shock scenario. In this contribution the main ingredients which were used to develop such model and the conclusions derived from GRB 190114C modeling will be presented. The current growing number of GRB detections in the VHE band will be exploited to perform initial population and systematic studies of GRBs detected in the VHE band testing the synchrotron and SSC external forward shock scenario.

The external forward shock scenario

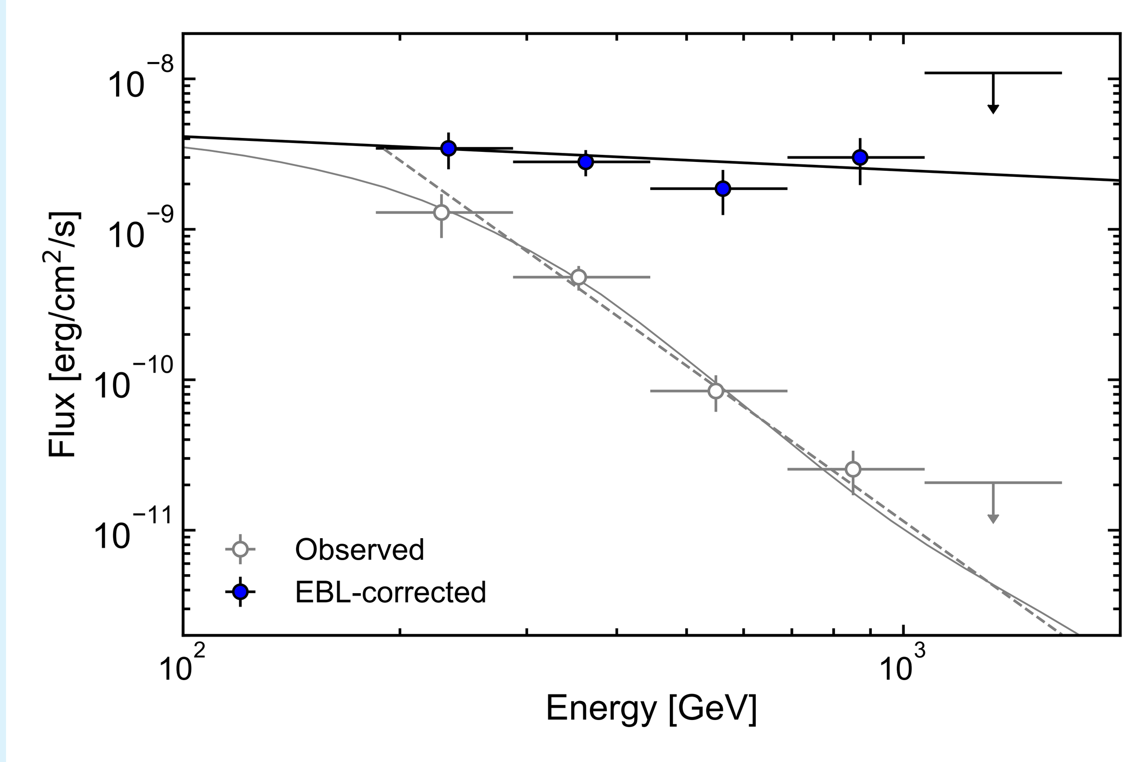
Radiation mechanisms generated by leptons and/or hadrons accelerated in shocks with different environmental conditions are believed to be responsible of the GRB emission[1,2,3,4]. The late-time long lasting TeV component is thought to be connected with the afterglow emission at lower energies and to have an external origin that is to be generated from external shocks. The most credible picture able to explain the multi-frequency emission from radio up to TeV is the synchrotron and SSC external forward shock scenario[5,6]. In this model the emission is generated from the interaction between a decelerating fireball and the circumburst external medium. The mechanism can be summarized as follows:

- During its dynamical evolution, the decelerating blastwave will encounter and shock the circumburst interstellar material
- The bulk energy of the decelerating blastwave is gradually converted into random kinetic energy produced at a shock from the interaction with the circumburst material.
- A fraction of this energy will go to the swept-up particles which will be accelerated and a fraction will be gained by the magnetic field
- The accelerated particles will then react emitting electromagnetic radiation.
- In presence of strong magnetic fields, the main responsible radiation mechanisms are thought to be the **synchrotron emission** and the **Inverse Compton (IC)** emission of the up-scattered synchrotron photons.



Modeling of afterglow emission is often performed with analytical prescriptions describing the framework of the synchrotron and SSC external forward shock scenario under several assumptions. More recently, numerical modeling[7,8,9] including general treatments of several leptonic or hadronic radiation mechanisms have also been developed. A set of free parameters describing the unknown properties of the shock microphysics, interstellar medium and initial conditions are introduced.

GRB in the VHE band



GRB 190114C spectral energy distribution[10].

Search for VHE emission component in GRBs have been performed by means of ground-based Cherenkov telescopes. Until 2019 no evidence for the existence of this component could be claimed. Then, after almost 20 years of investigation, the MAGIC and H.E.S.S. telescopes have announced the successful detection of VHE emission from a few events. At the current stage, four long GRBs have been clearly detected in the VHE domain:

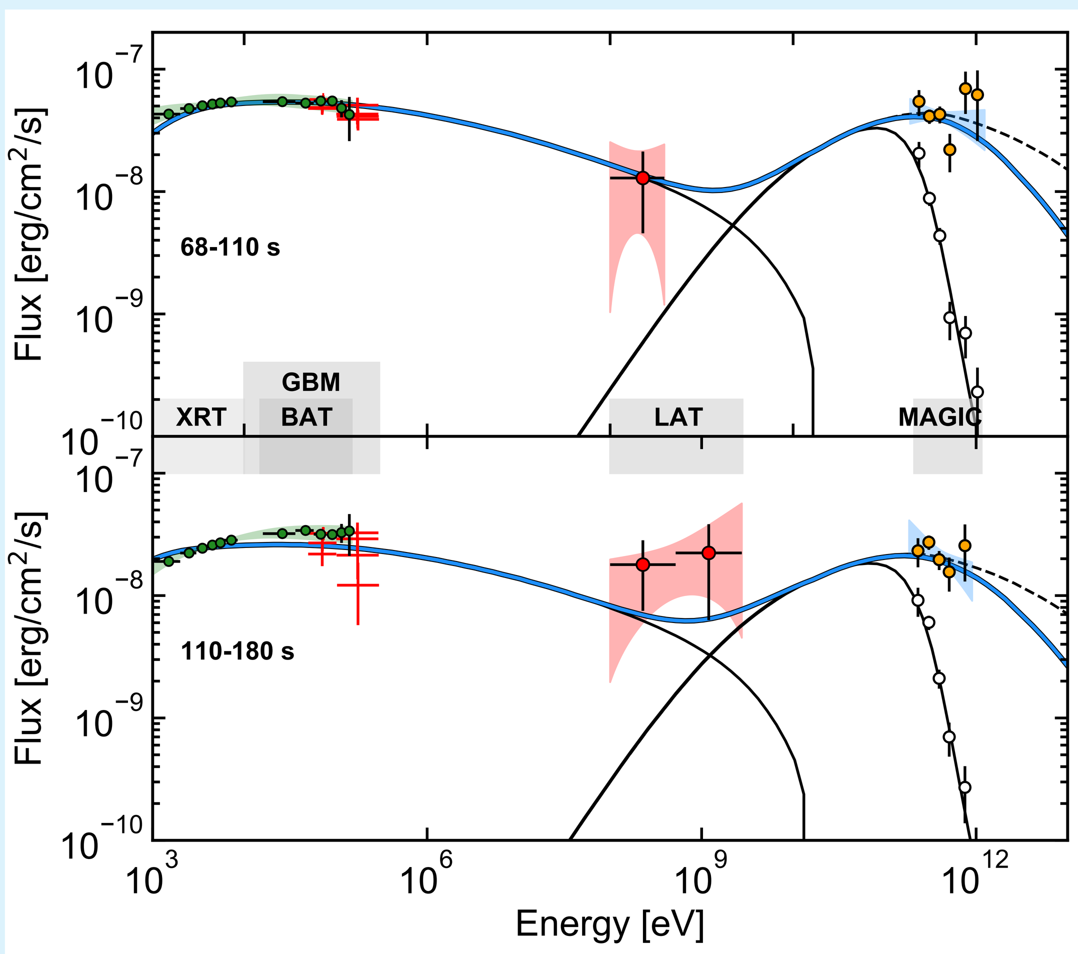
- **GRB 190114C**[10] and **GRB 201216C**[11] detected by the MAGIC telescopes
- **GRB 180720B**[12] and **GRB 190829A**[13] detected by the H.E.S.S. telescopes

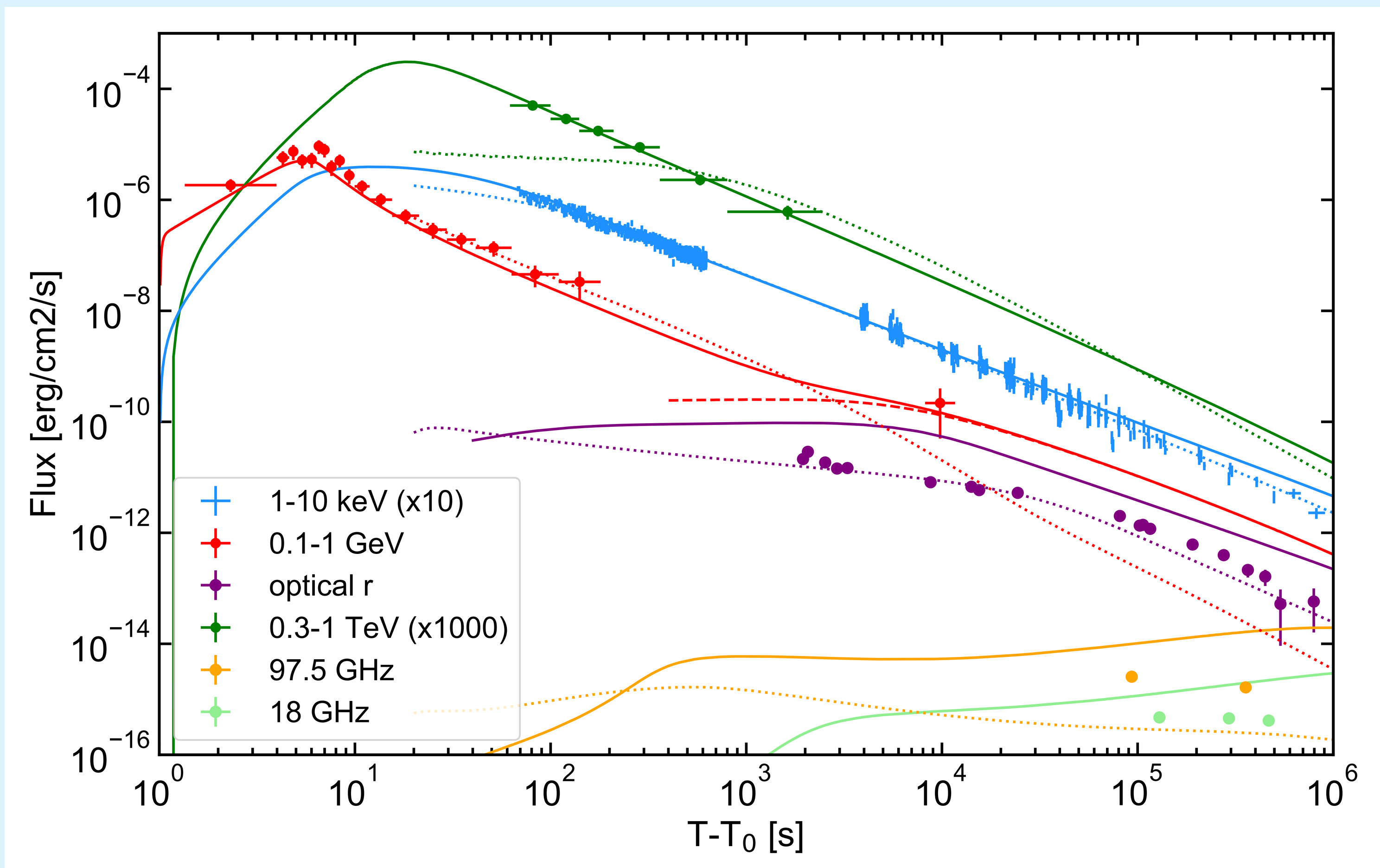
GRB 190114C is the first event for which an emission component reaching the TeV band was identified. A deep study of the evolution in time and energy of such emission component was then presented for the first time ever[14].
Evidences of an hint of gamma-ray signal have been also claimed by the MAGIC telescopes during the observations of the following events:

- short **GRB 160821B**[15]
- long **GRB 201015A**[16]

Modeling of GRB 190114C

The broadband dataset collected for GRB 190114C made possible to model for the first time ever the time-evolving spectral energy distributions and the light curves of the GRB multi-wavelength afterglow emission from radio up to TeV energies. A satisfactory description of the emission was obtained modeling the entire dataset with a numerical model reproducing the synchrotron and SSC emission within the external forward shock scenario. Additional mechanisms such as adiabatic losses and pair production mechanisms have been also included in order to properly reproduce the shape of the radiative output emission[14].





Left plot: modeling of GRB 190114C spectral energy distributions in two different time intervals. Observed (thin solid line) and deabsorbed (thick blue line) spectrum are displayed. The dashed line is the SSC component neglecting the effects of internal γ-γ opacity. Right plot: Modeling of GRB 190114C multi-wavelength light curves from radio up to TeV.[14]

The multi-frequency modeling of the spectral energy distribution (left plot) including emission from keV up to TeV band shows a double-hump structure. In this description the first hump peaking in the X-ray band is explained as the synchrotron component. Then, at higher energies, a distinct spectral component arises. This is interpreted as the radiation up-scattered through Inverse Compton by the same population of relativistic electrons responsible of the synchrotron emission at lower energies. As a result, a second hump peaking in the VHE band, and with a power comparable to that of synchrotron radiation is produced.
The light curve modeling (right picture) includes the entire multi-wavelength dataset from radio up to TeV energies. Two possible family of solutions explaining this broadband emission are displayed. The model showed with solid lines (same as in left plot) is optimized for the high energy radiation in the X-ray, GeV, and TeV band. It is obtained assuming an homogeneous constant-density external medium $n \propto R^0$. Dotted curves correspond to a better modelling of observations at lower frequencies and includes a wind-like scenario for the interstellar medium density $n \propto R^{-2}$. Nevertheless, this model fail to explain the behaviour of the teraelectronvolt light curve.

Conclusion and Prospects

After decades of searches, the recent detections of a VHE emission component have opened a new spectral window in the GRB observations allowing to investigate directly the theoretical framework thought to be responsible of this radiation. In particular, the studies performed on the time-evolving spectral distributions and light curves of GRB 190114C gave for the first time ever the possibility to test with unprecedented accuracy the involved emission mechanisms. The most plausible scenario explaining the multi-wavelength afterglow emission of GRB 190114C is the synchrotron and SSC external forward shock model. The free afterglow parameters adopted in the broadband modelling are similar to those one used for past GRB afterglow studies. This point towards the condition that a SSC component in the TeV band might be present in a large sample of GRBs. The following GRB detections during these last years support this statement. Such growing number of GRB detections in the VHE band will be exploited to test the SSC external forward shock scenario and investigate in more detail the observational and physical conditions which favour the detections of this energetic radiative component in GRBs.

References

[1] Sari et al., Spectra and light curves of gamma-ray burst afterglows. *Astrophys. J. Lett.* 497, 17–20 (1998). [2] Granot et al., The shape of spectral breaks in gamma-ray burst afterglows. *Astrophys. J.* 568, 820–829 (2002). [3] Panaitescu et al., Analytic light curves of gamma-ray burst afterglows: homogeneous versus wind external media. *Astrophys. J.* 543, 66–76 (2000). [4] Böttcher et al., High-energy Gamma Rays from Ultra-high-energy Cosmic-Ray Protons in Gamma-Ray Bursts, *The Astrophysical Journal*, 499, 2, L131–L134, (1998), [5] Sari et al., On the synchrotron self-Compton emission from relativistic shocks and its implications for gamma-ray burst afterglows. *Astrophys. J.* 548, 787–799 (2001). [6] Nakar et al., Klein–Nishina effects on optically thin synchrotron and synchrotron self-Compton spectrum. *Astrophys. J.* 703, 675–691 (2009). [7] Petropoulou et al., On the multiwavelength emission from gamma ray burst afterglows. *Astron. Astrophys.* 507, 599–610 (2009). [8] Pennanen et al., Simulations of gamma-ray burst afterglows with a relativistic kinetic code. *Astron. Astrophys.* 564, A77 (2014). [9] Asano, et al., Hadronic Models for the Extra Spectral Component in the Short GRB 090510, *The Astrophysical Journal*, 705, 2, L191–L194, (2009). [10] MAGIC Collaboration et al., Teraelectronvolt emission from the γ-ray burst GRB 190114C. *Nature*, 575(7783), 455–458, (2019), [11] Blanch, O., GRB 201216C: MAGIC detection in very high energy gamma rays, GCN.29075, (2020), [12] Abdalla, H., A very-high-energy component deep in the -ray burst afterglow, *Nature*, 575, 7783, 464–467, (2019), [13] H.E.S.S. Collaboration et al., Revealing x-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow, *Science*, 372(6546), 1081–1085, (2021), [14] MAGIC Collaboration et al., Observation of inverse Compton emission from a long γ-ray burst. *Nature*, 575(7783), 459–463, (2019), [15] Acciari, V. A. et al., MAGIC Observations of the Nearby Short Gamma-Ray Burst GRB 160821B, *The Astrophysical Journal*, 908, 1, (2021), [16] Blanch, O., MAGIC observations of GRB 201015A: hint of very high energy gamma-ray signal, GCN.28659, (2020)