Theoretical implications on the very high energy emission from GRB 190114C

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Since their discovery in the late 1960s Gamma-Ray Burst (GRB) emission has been deeply investigated with the help of the huge amount of data collected covering the entire electromagnetic spectrum. This large and broadband dataset was essential to constitute a general picture describing the GRB physics, revealing the most credible underlying physical processes and environmental conditions ongoing at the GRB site. A key leap in the comprehension of the GRB physics have been achieved recently, thanks to the detection of the newly energetic component in the Very High Energy (VHE, E $>$ 100 GeV) domain. The possible presence of a TeV spectral window in GRBs was predicted and theorized for several decades, but the first observational proofs of its existence were reached only in 2019 thanks to the discoveries claimed by the MAGIC and H.E.S.S. telescopes. GRB190114C was successfully detected in the TeV band by the MAGIC telescopes starting from around one minute after its trigger time and lasting for nearly 40 minutes. A successful follow-up campaign was performed and the multi-wavelength afterglow emission of the event was collected from 1 to about 2×10^{17} GHz. Such very broad dataset allows to perform unique studies on the radiation mechanisms and on the physical properties of such event. In this contribution I will describe the main results and the theoretical interpretations that have been derived from the multi-wavelength dataset of GRB190114C. In particular, the description of the TeV component detected by the MAGIC telescopes as produced via the Synchrotron Self-Compton (SSC) mechanism and its connection with the emission at lower energy bands will be presented. Such studies are a fundamental starting point for the interpretation of the current and upcoming events that will be observed in the VHE domain.

Keywords: Gamma-ray bursts; very high energy; synchrotron-self compton

1. Introduction

Gamma-Ray Bursts (GRBs) are transient phenomena produced during cataclysmic events such as the death of massive stars or the merging of binary compact objects like neutron stars and black holes.

The GRB electromagnetic radiation is characterized by initial rapid and irregular flashes bright in the keV-MeV band, the so-called *prompt* emission phase followed by a long-lasting broadband fainter emission, named *afterglow*. The duration of the prompt emission spans from milliseconds to thousands of seconds and is used to classify GRBs as *short* and *long* with a separation value of 2 s. The afterglow phase, which follows or partially overlaps with the prompt emission, is usually detectable within timescale of days, weeks or in some cases even months.

Because of its multi-wavelength nature, intense campaigns are performed to search for and follow this broadband emission from radio up to γ-rays, both with ground-based telescopes and space-born satellites. While the prompt emission mechanism is still unclear, the afterglow radiation from radio up to GeV is well described as synchrotron emission produced in the external forward shock scenario due to the interaction between the jet and the surrounding interstellar medium or stellar wind (depending on the progenitor). The possible extension of the GRB emission in the high energy (0.5 MeV $<$ E $<$ 100 GeV, HE) and to the very high energy domain (VHE, E $>$ 100 GeV) has always been one of the most debated open questions in GRB physics. The HE observations have revealed the presence of an emission component with peculiar temporal and spectral properties. The highest energy photons observed by Fermi-LAT are hardly to reconcile with the standard synchrotron afterglow scenario and hint the possibility that a new VHE emission component in GRBs is present.

A firm conclusion could be reached thanks to the observations performed by ground-based imaging Cherenkov telescopes. In particular, the MAGIC and the H.E.S.S. telescopes revealed unequivocally the presence of a VHE emission component in GRB afterglows up to TeV energies.[1] Such detections gave birth to unique studies covering several open topics of the GRB physics. In this contribution we report the analysis results and the theoretical implications derived from the TeV detection of GRB 190114C performed by the MAGIC telescopes. The interpretation of the full GRB 190114C multi-wavelength dataset with the synchrotron and Synchrotron-Self Compton (SSC) scenario and the intimate connection between the TeV emission component and the lower energy ones is presented.[2,3]

2. TeV detection and interpretation of GRB 190114C

GRB 190114C is a long GRB triggered by Swift-BAT and Fermi-GBM space instruments on 14 January 2019, 20:57:03 UT (hereafter T_0). The event was detected also by several other space instruments, namely Fermi-LAT, Swift-XRT, Swift-UVOT, AGILE, INTEGRAL/SPI-ACS, Insight/HXMT, and Konus-Wind. Triggered by space satellite alerts, the event was then followed-up and detected by

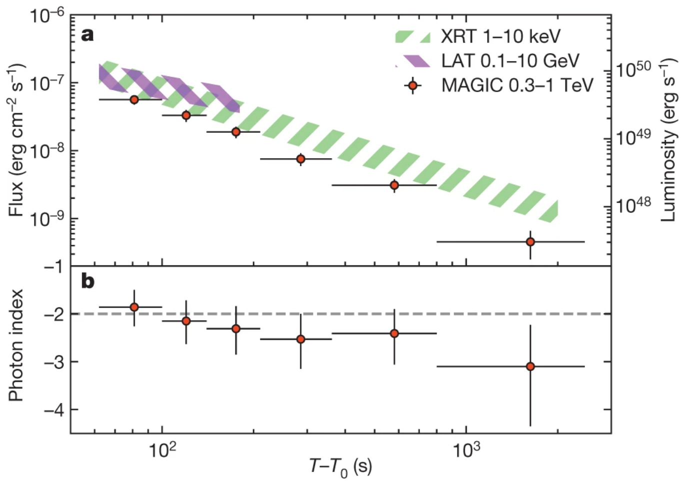

Fig. 1. **a**: MAGIC (red circles), XRT (green band) and LAT (red band) light curves. **b**: temporal evolution of the intrinsic spectral photon index.[2]

the MAGIC telescopes in the VHE band and several optical-NearInfraRed (NIR) and radio ground based telescopes. The Nordic Optical Telescope and the Gran Telescopio Canarias gave a redshift estimation of $z = 0.4245 \pm 0.0005$.

The timeline of the MAGIC observation can be described as follows:

- the Swift-BAT alert was received by the MAGIC automatic alert system at T_0 + 22 s. The alert was validated, the event tagged as observable and the automatic fast repositioning procedure started;
- the telescopes reached the target and started tracking at T_0 + 50 s;
- the data acquisition started receiving the first events at T_0 + 57 s and operated stably from T_0 + 62 s;
- observation lasted until T_0 + 15912 s when a zenith angle of 81.14° was reached.

The observation was performed in good weather conditions and in presence of the Moon, resulting in a night sky background approximately 6 times higher than the standard dark night conditions.

The analysis of the MAGIC dataset was performed with unprecedented accuracy performing many checks and tests to investigate the behaviour of the subsystems during the repointing and data taking. Moreover, several dedicated MC sets were produced in order to match the GRB observational conditions in the most precise way. The result of the offline analysis shows a clear detection above the 50 sigma level in the first 20 minutes of observation.

The light curve for the intrinsic flux corrected for the Extragalactic Background Light (EBL) absorption in the 0.3–1 TeV range was derived. A comparison of this light curve with the simultaneous X-ray and HE emission is shown in Figure 1.

From the evolution of the light curve and the comparison with the lower energy band emission it is possible to derive clues on the origin and the amount of power radiated in the TeV component. The TeV light curve is well described with a simple power-law temporal decay with index $\beta = 1.60 \pm 0.07$. A similar behaviour can also be seen in the X-ray and HE band. These properties, together with the absence of breaks, cutoffs or irregular variability, support the conclusion that the observed VHE emission component belong to the afterglow phase. Nevertheless, the presence of a subdominant prompt component cannot be excluded.

The comparison of the simultaneous light curves shows also that the radiated power in the TeV band is mostly comparable, within a factor of about 2, with the X-ray and HE bands. This means that a non-negligible fraction of energy is radiated in the TeV band. A rough estimate, calculated assuming that the onset of the afterglow is at $T_0 + 6$ s[4] and following the time evolution estimated by the MAGIC light curve is of around $\sim$ 10% of the isotropic-equivalent energy of the prompt emission E_{iso}.

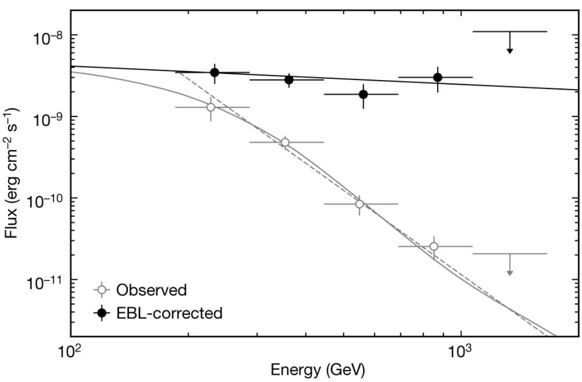

Fig. 2. GRB 190114C Observed (grey open circles) and intrinsic (black filled circles) spectral energy distribution in the time interval $T_0 + 62$ s and $T_0 + 2454$ s. The best fit power-law functions (black solid line and dashed grey line) and the EBL attenuated curve (solid grey line) are also shown.[2]

In Figure 1 also the temporal evolution of the intrinsic spectral photon index α_{int} of the TeV differential photon spectrum is shown. A constant value of $\alpha_{int} \approx -2$ is consistent with the data, considering the statistical and systematic errors. As a result, throughout the MAGIC observation, no spectral variability can be claimed. This value indicates that the radiated power is equally distributed in the 0.3-1 TeV energy range.

The observed and EBL-corrected spectral energy distributions in the 0.2-1 TeV energy range and ($T_0 + 62$ s - $T_0 + 2454$ s) time interval were also derived. Both the spectra are fitted with a simple power-law with indices $\alpha_{obs} = -5.34 \pm 0.22$ and $\alpha_{\rm int} = -2.22^{+0.23}_{-0.25}$ respectively for the observed and EBL-corrected spectrum.

This result states that the VHE component observed by MAGIC is extended up to TeV energies. Moreover, the steep observed spectrum obtained certificates the strong effect of the EBL absorption (a factor of $\sim$ 300 at 1 TeV) in shaping the GRB spectra in the VHE domain.

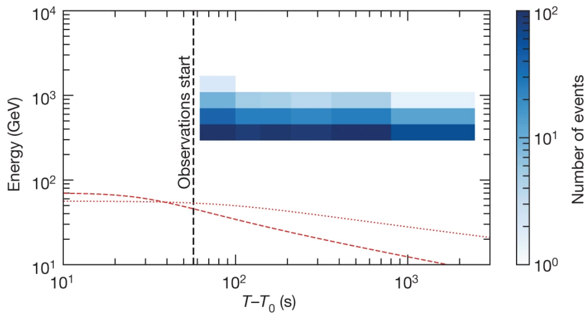

Fig. 3. Distribution of the number of GRB 190114C γ-ray events observed by MAGIC binned in time and energy and colour-coded. The synchrotron burnoff limiting curves are also displayed with two different assumptions for the external medium surrounding the GRB site: constant-density interstellar medium (dotted curve) and wind-like scenario (dashed curve).[2]

The similarities observed between the X-ray and the TeV light curves point towards the possibility that the same radiation mechanism is responsible for both components. Nevertheless, we proved that the TeV component cannot be interpreted as a simple extension in energy of the electron synchrotron emission mechanism. Indeed, in this scenario the energy of the accelerated electrons and hence of the synchrotron photons emitted is limited to a maximum value. This value can be estimated by equating the acceleration timescale and the synchrotron losses timescale, which dominates the electron energy losses. As a result, the maximum synchrotron photon energy, also called *synchrotron burnoff limit* is estimated as $E_{\rm syn,max} \sim 0.1\Gamma_{\rm b}(t)/(1+z)$ GeV where $\Gamma_{\rm b}(t)$ is the Lorentz bulk factor of the GRB jet and z is the redshift. In Figure 3 we compared the energy of the observed photons by MAGIC binned in time and energy with $E_{\rm syn,max}$ assuming two possible scenarios for the dynamical evolution of the GRB blast wave. It can be clearly seen that events detected by MAGIC are well more energetic than $E_{\rm syn,max}$ in both scenarios. This gives a strong proof that a different radiation mechanism than electron synchrotron radiation must be claimed to explain such VHE emission component in GRB 190114C.

3. Multi-wavelength afterglow modeling

A multi-wavelength interpretation is fundamental for an in-depth study of the properties of the TeV emission and its connection with the lower energy band radiation. GRB 190114C emission was detected across 17 orders of magnitude in energy and

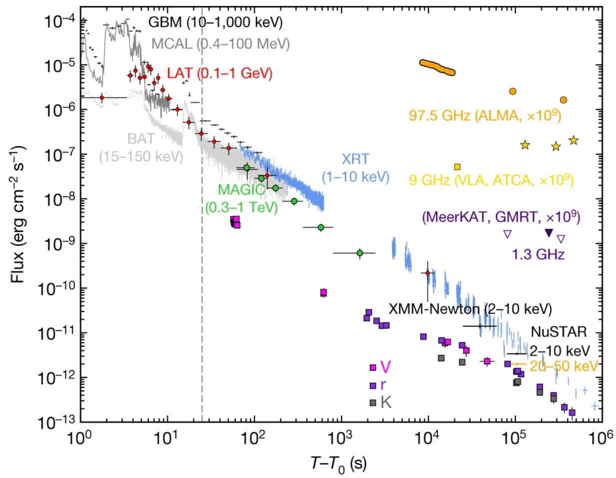

Fig. 4. Broadband light curves of GRB 190114C. Data from radio up to γ-rays are included. The vertical dashed line marks approximately the end of the prompt phase, identified as the end of the last flaring episode.[3]

by more than 20 instruments both from ground and in space (see Figure 4). In particular, the simultaneous data collected in a few time intervals in the X-ray (XRT, BAT, GBM), HE (LAT) and VHE (MAGIC) domain allow to build multi-wavelength time-binned spectra (see Figure 5). In the first time interval (68-110 s) the usual synchrotron peak flux is located in the X-ray band. Subsequently, in the HE band a decreasing flux behaviour is observed. Then, the VHE data implies the presence of a second peak in the flux and a spectral hardening for energies $E > 0.2$ TeV. This behaviour can be explained only if we assume that the TeV emission is not an extention of the X-ray synchrotron emission component but it is produced by a different radiation mechanism.

The most credible scenario able to describe consistently the multi-wavelength data is the *synchrotron and SSC external shock scenario*. In this picture, the SSC radiation mechanism produces the TeV photons while the synchrotron emission can explain the lower energy band radiation. The distribution of accelerated electrons emitting the synchrotron radiation are also responsible for the up-scattering of the same synchrotron photons through inverse Compton mechanism. As a result, a second spectral component peaking in the VHE band is generated. The afterglow emission is usually well described through external shocks. SSC radiation at TeV level can be also produced in internal shock synchrotron models for the prompt emission. However, for GRB 190114C it was estimate that it can only partially contribute ($\lesssim 20\%$) for the flux emitted at early times ($\lesssim 100$ s). As a result, the SSC radiation in the afterglow scenario is the most viable process.

The validity of this scenario was tested thanks to a numerical modeling. The full multi-wavelength dataset was modelled with a numerical code reproducing the

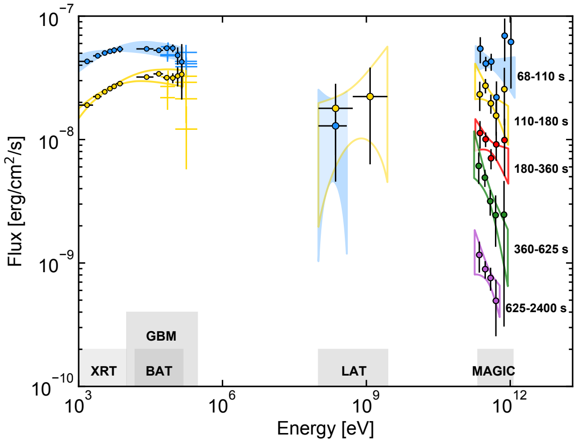

Fig. 5. Multi-band SEDs in five different time intervals. MAGIC data analysis results are corrected for the EBL attenuation. MAGIC and LAT contour regions are drawn from the 1σ error of their best-fit power-law functions. For Swift data, the regions show the 90% confidence contours for the joint fit for XRT and BAT, obtained by fitting a smoothly broken power law to the data.[3]

synchrotron plus SSC radiation emitted in the external forward shock afterglow scenario. In Figure 6 the modeling for two time intervals and for the X-ray, HE and VHE bands is shown. The numerical code solves the time-evolving electron distribution and calculates the corresponding photon emission covering the entire electromagnetic spectrum. The following radiation processes are considered: electron synchrotron emission and self-absorption, SSC emission, adiabatic losses, γ-γ absorption and emission from pairs. A set of inputs parameters containing some assumptions due to unknown properties of the acceleration process, of the shock microphysics, of the external medium and of the GRB jet and the initial conditions of the system are given in the code. The soft spectrum derived from the MAGIC dataset constrain the peak of the SSC component to be below 200 GeV. Such condition is obtained assuming that the SSC process is in Klein-Nishina regime and the γ-γ internal absorption has a non-negligible contribution in shaping the higher energy tail of the VHE spectrum.

Acceptable modeling of the multi-wavelength afterglow spectra have been found with an initial isotropic-equivalent kinetic energy of the blastwave $E_k \gtrsim 3 \times 10^{53}$ erg. The electron and magnetic field equipartition parameters are respectively $\varepsilon_e \approx 0.05-0.15$ and $\varepsilon_b \approx 0.05-1\times10^{-3}$, the density of the external medium is $n \approx 0.5-5$ cm^{-3} and the distribution of the accelerated electrons is described with a power-law of index $p \approx 2.4-2.6$. This set of values for the GRB afterglow parameters is similar to the one used for past GRB afterglow studies at lower frequencies. This is an indication that the SSC component can be a relatively common process for GRB afterglows.

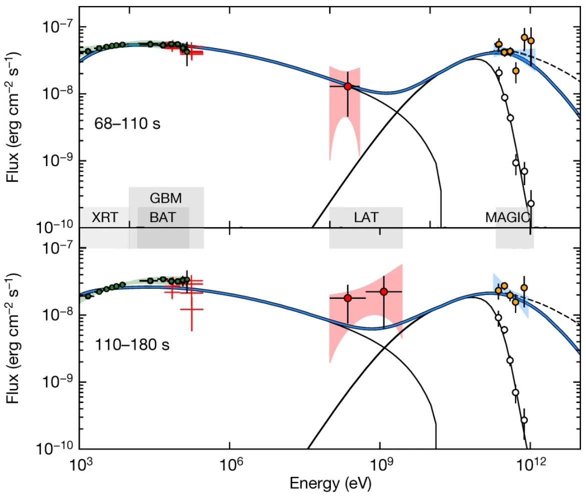

Fig. 6. Modeling of GRB 190114C spectral energy distributions in two different time intervals. Observed (thin solid line) and deabsorbed (thick blue line) spectrum are displayed. The dashed line is the SSC component neglecting the effects of internal γ-γ opacity.[3]

4. Conclusions

Observation and detection of GRB 190114C is a key milestone for the study and the interpretation of GRB physics. After decades of searches, the unambiguous discovery of a TeV component in GRBs made it possible to address for the first time ever several open questions. The newly open TeV spectral window also gives rise to new challenges for the observation and interpretation of GRBs.

A complete multiwavelength modeling of the GRB 190114C data covering the entire electromagnetic spectrum from radio up to TeV was presented. The full evolution of the afterglow emission was interpreted with the synchrotron plus SSC external forward shock scenario. The afterglow parameters used in the modeling of the X-ray, HE and VHE data have relatively common values, similar to those used in previous studies on GRBs where VHE emission was not detected. When evolving this solution to later times (see Figure 7) the optical and radio emission is overpredicted with respect to the observations. This inconsistency between the data and the modeling can be interpreted as an indication that some of the fixed parameters of the afterglow theory (e.g. the electron and magnetic field equipartition parameters) may evolve in time.

The intrinsic properties of GRB 190114C are not so exceptional when compared with the sample of the observed long GRBs. Despite being an energetic event (the isotropic-equivalent energy from the prompt is $\approx 3 \times 10^{53}$), it lies in the highest 30% distribution in energy for long GRBs.[5] This suggests that a larger sample of GRBs can have a detectable TeV component. On the other hand, favourable observational conditions and redshift play a crucial role in order to make TeV detections possible.

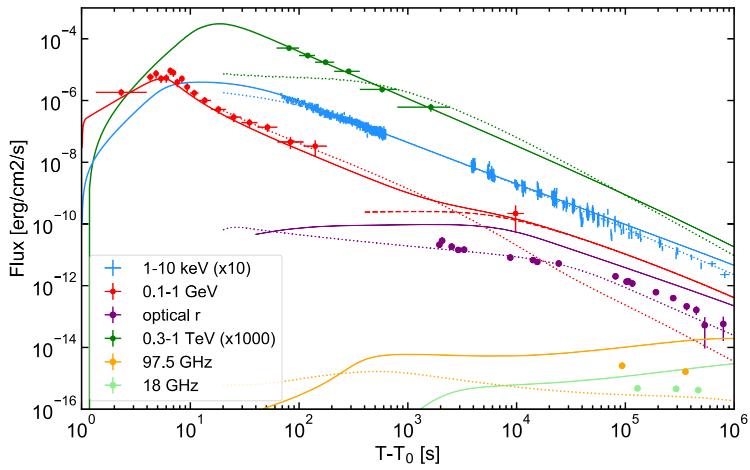

Fig. 7. Modeling of GRB 190114C afterglow light curves from radio up to TeV. Two different sets of parameters, respectively displayed in solid and dotted lines are compared to the observations. The former one is optimized for the X-ray, GeV and TeV data while the latter one well reproduces the late time optical modeling but do not explain the early time TeV emission. The dashed red line indicate the SSC contribution in the 0.1-1 GeV band.[3]

This was proved by the TeV detections of other three long GRBs: GRB 180720B,[6] GRB 190829A[7] and GRB 201216C.[8] These discoveries showed that TeV detections can be possible even at late times (hours on even a day after the trigger like in the case of GRB 180720B and GRB 190829A), or in low-luminosity events ($E_{iso} \approx 3 \times 10^{50}$ in GRB 190829A), or at higher redshift ($z = 1.1$ for GRB 201216C). The first population studies of GRBs at VHE will provide the possibility to investigate the conditions which favour a TeV detection.

The TeV photons detected from GRB 190114C were also used to give insights on some fundamental physics questions. An example is given by the study and the bounds derived on the Lorentz invariance violation effect.[9]

Furthermore, the ongoing observations of GRBs in the VHE domain will be fundamental to state the presence of a TeV emission component in short GRBs (a hint of detection, but still not conclusive, was claimed for GRB 160821B[10]) or during the prompt emission phase. Short GRBs are known to be linked with gravitational wave events. Therefore, the detection of a TeV emission component could give information on the structure of GRB jets as well as on the geometry of the merger event. The detection of TeV emission in the prompt emission phase shall provide essential information on the radiation mechanisms involved which are still unknown.

Further detections of GRBs in the VHE domain will be also useful to test the current most credible scenario for the TeV afterglow emission, namely the SSC external forward shock scenario. At the current stage, the results published for GRB 190114C,[3] GRB 180720B[6] and GRB 190829A[11] can be satisfactorily interpreted with the SSC scenario. Nevertheless, several open questions and assumptions on the acceleration process, shock microphysics and environmental condition are still unclear.

In this evolving context the robust results obtained from the analysis and the interpretation of GRB 190114C will be a reference point for future studies of the properties of the VHE emission component in GRBs.

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