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The new age of Gamma Ray Bursts: physics and multi-messengers

G. Ghisellini[1], G. Ghirlanda[1], S. Covino[1], P. D'Avanzo[1], S. Campana[1], A. Melandri[1], M. G. Bernardini[1], O. S. Salafia[1,2], M. Colpi[2], M.E. Ravasio[1,2], M. Toffano[1,3], G. Oganeysan[4], A. Celotti[5], and F. Fumagalli[1,2]

[1] INAF – Osservatorio Astronomico Brera, Via Bianchi 46, I-23807 Merate, Italy.
[2] Univ. di Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy
[3] Università dell'Insubria, Via Valleggio 11, 22100 Como, Italy
[4] Gran Sasso Science Institute, Viale F. Crispi 7, I-67100, L'Aquila (AQ), Italy
[5] SISSA, Via Bonomea 265, 34136 Trieste, Italy

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Abstract. The era of multimessenger astronomy, born on 17 August 2017, strongly revived the field of short Gamma Ray Bursts (GRB). Other similar events in the following observing runs of LIGO/VIRGO, although in run O3 the event candidates associated with be neutron star - neutron star mergers were not found to be electromagnetic sources. In any case, we have pursued theoretical studies (spectrum, contributions of afterglow/kilonova, rates) to continue to be at the forefront of research in this field. The study of the prompt emission of both short and long GRBs made an unexpected turn recently, by some of our team, who discovered that the hard X-ray prompt spectrum can be explained by synchrotron radiation, but by incompletely cooled electron population, implying small magnetic fields and yet inefficient inverse Compton. We needed a confirmation for larger GRB samples, and a convincing explanation. These issues were actively pursued in two main ways: 1) leading to a number of paper assessing the universality of a new spectral feature in the spectrum of the prompt emission, and 2) leading to a new proposal for the emitting particles, that could be relativistic protons instead of electrons. For all the above issues we used XMM, Chandra, Fermi/GBM and Fermi/LAT.

Key words. Gravitational waves – Radiation mechanisms: non-thermal – Gamma-ray burst: general – Gamma rays: general

1. Introduction

Starting in 2017 the field of Gamma Ray Bursts (GRBs) witnessed profound renovation due to key astrophysical discoveries. The two leading breakthroughs were (1) the first, and still only, detection of the electromagnetic emissions following the gravitational wave (GW) signal produced by the merger of two neutron stars and (2) the detection of emission at Tera electron–Volt energies in few GRBs by Cherenkov Telescopes (Acciari et al. 2020, Abdalla et al. 2019). The opening of the Multi–Messenger era with the association of GRB

170817A (Abbott et al., 2017) and the kilonova AT2017gfo (Coultier et al. 2017) with GW 170817A (Abbott et al. 2017) showed the great potential of combining the two signals to unveil the physics of compact object mergers, constrain cosmological parameters and perform fundamental physics tests. GRBs detected at TeV energies (now comprising four events) represent a unique tool to unveil the nature of the emission mechanism, to probe particle acceleration in extreme environments and to test the GRB standard model (e.g. Nava et al. 2021).

We summarize in §3 the main scientific results that we obtained in the last three years related to the study of GRBs in light of the newly born multi–messenger era the new observational results and theoretical interpretations about their high energy emission.

2. Results

2.1. Gravitational wave counterparts

For GRB/GW 170817 our team had a leading role in the discovery, characterisation and interpretation of the multi–wavelength emission components. In particular, we participated in the discovery the first X–ray counterpart of a GW event through dedicated Chandra X–ray observations (Troja et al. 2017) and interpreted its broad band emission as the first evidence of an off-axis jet from a short GRB (Salafia et al 2020). We discovered the peak of the afterglow emission (Fig. 1–left) thanks to dedicated XMM-Newton observations at ∼ 150 days after the merger (D'Avanzo et al. 2018) also acquiring compelling evidence for the possible signature of a long–lived NS remaining after the merger (Piro et al. 2019) and followed the emission until its possible very late uprise (Troja et al. 2022). We performed high resolution spectroscopy of the first ever kilonova emission (Pian et al. 2017, Troja et al 2017), providing a key to explain the origin of high elements produced through rapid neutron capture within the merger ejecta. We first explored alternative models for the interpretation of the very early high energy emission (Salafia et al. 2018) and developed high performance computing models for the afterglow emission from GRB relativistic jets (Salafia et al. 2020).

Some aspects of the physics of both short and long GRBs are still not understood. In particular, there is some uncertainties about the origin and structure of their jets (homogeneous or structured) and the nature of the emission we see (prompt, afterglow, kilonova and possibly cocoon). The lesson learned from GRB 170817 is that only by combining high energy data collected by Fermi, Swift, XMM-Newton and NuSTAR with optical–through-radio follow up is the key to break degeneracies among source parameters.

One of the key question raised by the multi–wavelength photometric sampling of the afterglow light curve of GRB 170817 is whether a jet successfully emerged from the dense circum–merger ejecta (Fig. 1–left). We organized and led a worldwide VLBI radio observation leading to the detection of a compact radio emission at 207.4 days (Fig. 1–right) which can be interpreted as the signature of a relativistic jet emerging from the kilonova ejecta (Ghirlanda et al. 2019).

The still open question regards the origin of the jet structure and whether this is universal (e.g. Salafia et al. 2015). The propagation of the jet within the dense merger ejecta until break out could imprint a typical structure to the jet itself (Fig. 2) with a quite steep decrease of the energy and bulk Lorentz factor with increasing off-axis angle (Salafia et al. 2020).

This model successfully explains the luminosity distribution of short and long GRBs in a unified universal jet structure scenario (Pescalli et al. 2015; Salafia et al. 2015). The prompt and afterglow properties of GRB 170817 if it were observed along its jet would resemble that of its siblings, namely cosmic short GRBs (Salafia et al. 2019). The still open issue is related to the nature of the prompt emission process and its possible angular structure which could account for the relatively hard spectrum observed in this event. Prompt X–γ ray observations are fundamental to this aim (Ghirlanda et al. 2021).

GRB/GW 170817 showed the invaluable richness of EM-GW information: our knowledge of jets in short GRBs, so far indirectly

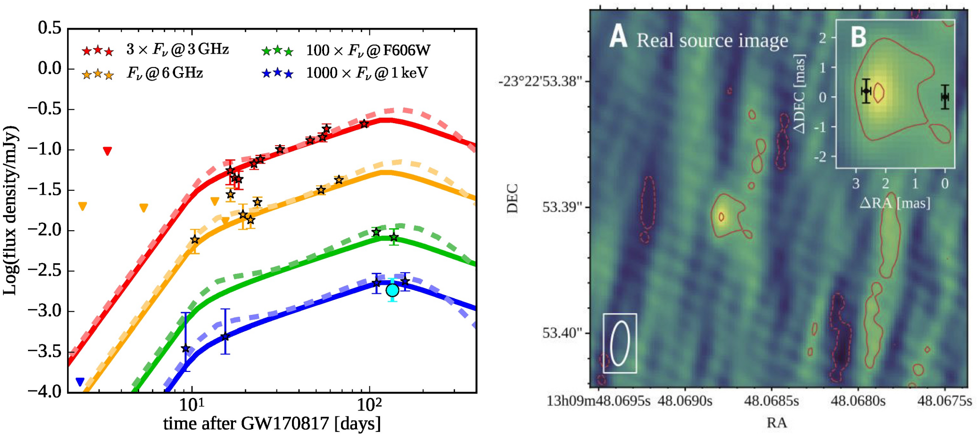

Fig. 1. *Left:* Multi–wavelength light curve of GRB170817 (adapted from D'Avanzo et al. 2018) showing the two possible interpretation of the emission arising from a structured jet (solid lines) or from a nearly isotropic outflow (dashed lines). The cyan symbol shows the XMM–Newton observation revealing the peak of the X–ray afterglow light curve. *Right:* radio image of the source at 207 days and source displacement (insert) with respect to bracketing observations. Adapted from Ghirlanda et al. (2019).

studied in very few events (e.g. Fong et al. 2015, Troja et al. 2016), was revolutionised and required the development and application of the more physically sound structured jet model (e.g. Rossi et al. 2002; Salafia et al. 2015). On the other hand, up to now GRB 170817 remains the only event revealed both gravitationally and electromagnetically.

To remain at the forefront of research we must study – in general – the physics of the merging, the interaction between the jet and the kilonova ejecta in developing the jet structure, the jet parameters in a broad variety of possible configurations. Future GW-EM events could constrain key physical processes at the base of the GRB phenomenon like the disk–to–jet power conversion process (Salafia & Giacomazzo, 2021). The awaited next discovery is the electromagnetic counterpart of black hole neutron star mergers (e.g. Barbieri et al. 2020), of which there are currently two GW detected candidates (Abbott et al. 2021). In particular current modelling of the expected electromagnetic counterparts are aimed at identifying key signatures of the different nature of the binary components (Barbieri et al., 2019).

2.2. Prompt emission mechanism.

Some members of our team (Oganesyan et al. 2017; 2018; Ravasio et al. 2018) were among the first to discover that the prompt emission of bright GRBs presents a very hard component (i.e. $F(\nu) \propto \nu^{1/3}$) that can be interpreted as the synchrotron emission of a distribution of electrons with a low energy cut-off. At higher energies, instead, the spectrum is consistent with cooling electrons (i.e. $F(\nu) \propto \nu^{-1/2}$). The time integrated spectrum of GRB 160625B as studied in Ravasio et al. (2018) is reported in Fig. 3. At low energies, between the two power law segments, a break occurs which can be identified as the synchrotron cooling frequency. These results, corroborated by the independent analysis of Swift/BAT+XRT data (Oganesyan et al. 2017, 2018, 2019) and Fermi/GBM data (Ravasio et al. 2018, 2019, see also Burgess et al. 2019), highlight a typical separation by a factor ∼5–10 between the low energy break (i.e. separating the $\nu^{1/3}$ and the $\nu^{-1/2}$ power laws) and the peak of the νF_ν spectrum. Furthermore (Ravasio et al. 2019) the value of the low break energy does not evolve considerably during the burst.

Despite these results, most GRB prompt emission spectra are fitted by the Band func-

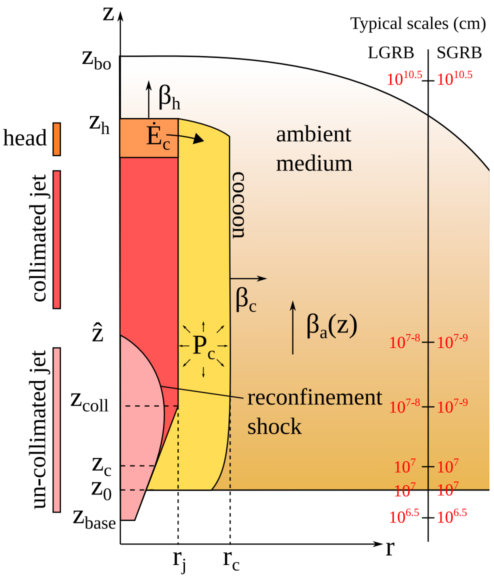

Fig. 2. Sketch of the various components of the jet propagation model, with some key quantities annotated. All quantities are defined and described in Salafia et al. (2020). Typical radii (order of magnitude in cm) are shown in red on the right, corresponding to the progenitors and average jet properties we employ when computing our synthetic jet populations (note that the collimation-related radii z_c, $z_{\rm coll}$ and change during the jet propagation). From Salafia et al. (2020).

tion which has only one break (corresponding to the peak of the νF_ν spectrum) and the spectral slope below the break is ~ -1. In Toffano et al. (2021) we have shown that a larger fraction of *Fermi* GRB spectra could be consistent with synchrotron typical shape (as in Fig. 3). However, the spectral signal to noise ratio and the degradation of the instrumental response at the edges of its nominal energy range seems to be main limitation for a systematic identification of synchrotron like spectra in current GRB databases. Experimental concepts like the X–Gamma ray Imager and Spectrometer on board THESEUS (Amati et al. 2018) should considerably improve the sample of GRBs with break (Ghirlanda et al. 2021).

These results strongly suggests that the emission is synchrotron, after decades of debate. However, we are facing a great challenge

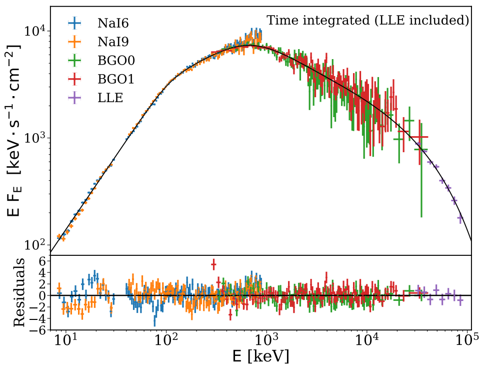

Fig. 3. GRB 160625B. *Fermi* spectrum (GBM+LAT data) fitted with a double smoothly broken power law function with a high energy exponential cutoff. The slopes of the power law segments below the peak of νF_ν spectrum are consistent with synchrotron values. From Ravasio et al. (2018).

(Ghisellini et al. 2001): how is it possible that electrons in the prompt phase do not cool completely in a very short time? Re-acceleration leads to a pile up, not observed. The magnetic field must be small, and yet the inverse Compton is not dominant. This leads to large sizes, but we are limited by the onset of the afterglow and by the rapid variability. Some of the pillars of the standard scenario must be revisited, e.g. combining data analysis (from the soft X–ray to the gamma rays) with models of the prompt emission. We proposed proton synchrotron as a promising mechanism to solve the incomplete cooling puzzle (Ghisellini et al. 2020). This solution allows a typical cooling timescale of the relativistic protons around one second for magnetic field $B \sim 10^6$ G. Although very promising, this solution is not problem–free, since the slow cooling timescale contrasts with the variability timescale (~ 10 ms). Larger magnetic field are then required, but these increase the total power demand, implying a larger Poynting flux. On the other hand, we consider this proposal as a very intriguing one to be studied further.

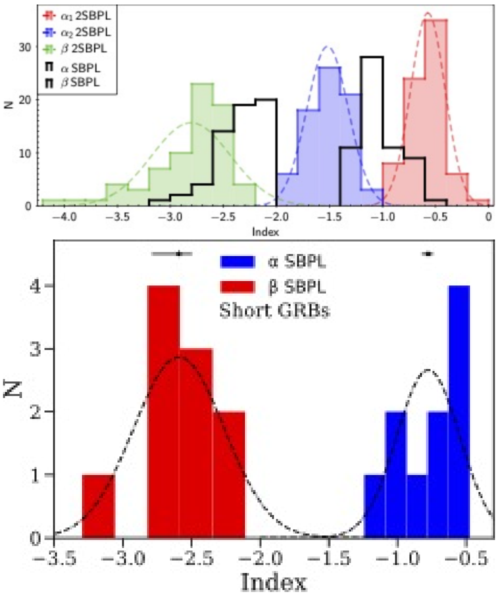

Fig. 4. Top panel: Distribution of the spectral indices, [α_1 (red), α_2 (blue), and β (green)] for the time-resolved fits of the eight long GRBs showing a spectral break. Gaussian functions showing the central value and standard deviation of the distributions are overlapped to the histograms (colour-coded dashed curves). The black empty histograms represent the distributions of the two photon indices α and β of the Band model. Bottom panel: distributions of the spectral indices α and β for all ten short GRBs. In this case, α is similar to α_1 of the long GRBs. Gaussian functions showing the mean value and standard deviation are overplotted on the histograms. From Ravasio et al. (2019).

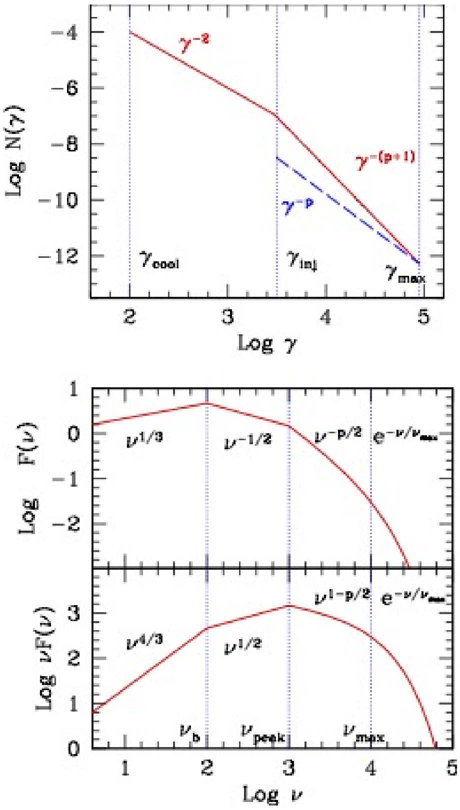

Fig. 5. Top panel: schematics of the particle distribution responsible for the spectra of the bottom two panels. The dashed blue line corresponds to the injected [$Q(\gamma)$] distribution. The characteristic Lorentz factors and frequencies are labelled. Bottom two panels: sketch of synchrotron spectra that should correspond to the $N(\gamma)$ of the top panel. From Ghisellini et al. (2020).

2.3. High energy LAT emission.

A sizeable fraction ~ 6% of GRBs detected by the GBM on board Fermi are also detected by LAT at >100 MeV (Ajello et al. 2019). This emission lasts much longer than the prompt phase and often shows a harder spectrum than the extrapolation of the energy part of the prompt emission spectrum. We have proposed it is afterglow emission (Ghirlanda et al. 2010; Ghisellini et al. 2010) and we showed that it can be used to derive the bulk Lorentz factor and thus intrinsic (comoving) properties of the bursts (Ghirlanda et al. 2012). The compelling question now becomes weather this is synchrotron or self-Compton. The very recent detection of GRB 190114C by MAGIC above 300 GeV starting ~60 seconds after the prompt, combined with the stringent upper limits provided by *Fermi*/LAT give strong evidence of an SSC component where MAGIC samples the Inverse Compton peak (MAGIC collaboration, 2019, Nature, 575, 455). This interpretation is further confirmed by the modelling of the multi–wavelength afterglow emission (MAGIC collaboration, 2019).

We have shown that the LAT data, recently expanded to cover the energy down to 30 MeV

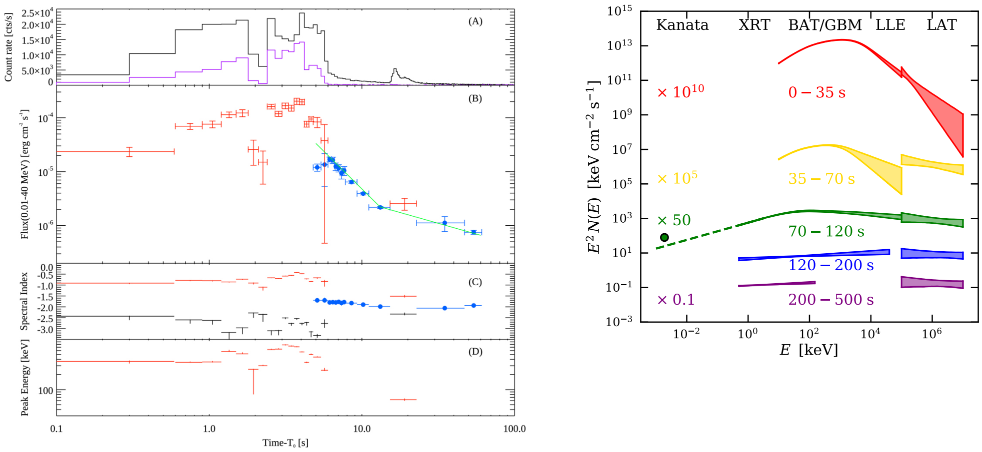

Fig. 6. *Left:* Spectral evolution of GRB 190114C. Panel A: count rate light curve (NaI: black solid line; BGO: purple. Panel B: the red symbols are the prompt emission, the blues ones are the afterglow, whose flux peaks around 6 s. 1σ errors are shown. Panel C: temporal evolution of the spectral photon indices of the prompt (red and black symbols) and of the afterglow (blue symbols). Panel D: evolution of the peak energy ($E_{\rm peak}$) of the prompt. From Ravasio et al. 2019. *Right:* Evolution of the SED of GRB 180720B. Each spectrum corresponds to the labelled time interval. Different SED have been arbitrarily normalized for presentation purposes. Top labels denote the instruments providing data in the corresponding energy ranges. From Ronchi et al. (2020).

with the LAT Low Energy - LLE - data, are fundamental to disentangle the afterglow emission from the fading prompt.

In two GRBs detected at TeV energies by Cherenkov telescopes (MAGIC and HESS) we have shown how the LAT data provide important information for the interpretation of the VHE emission. Through a time resolved spectral analysis, Ravasio et al. (2019) highlighted the presence of the afterglow component dominating the energy range $>$ 10 MeV while the prompt emission is fading (Fig. 6 left panel - blue symbols).

In the case of GRB 180720B (Ronchi et al. 2020) we could study the full evolution of the prompt to early afterglow transition and show (Fig. 6, right panel) that the afterglow emission dominates from ∼70 s the full spectral range from the optical to the GeV energy band. Furthermore, the temporal evolution of the LAT measured flux, interpreted as afterglow, allowed us to estimate a bulk Lorentz factor of a few hundred.

3. Conclusions

The next run of LIGO/VIRGO, with the a factor 5 of improved sensitivity (Abbott et al. 2020) of the gravitational antennas, promises to yield a factor ∼100 of gravitational events. The addition of the new gravitational antennas should shrink the typical error box of the event location. Therefore is very importance to continue to refine our predictions about the properties of neutron star-neutron- star as well as the neutron star-black hole mergers. With only one of these events, our knowledge underwent a quantum jump, but we should nevertheless be prepared to surprises. This was and will continue to be, the aim of our work about multimessenger astronomy.

The issue of what produces the prompt emission continues to be a challenge, despite (and partly because of) the recent observational proof that it is synchrotron in origin. More ideas are needed.

And finally, the GeV–TeV emission of GRBs, at last detected at these energies, promise to settle long debated questions as: it is prompt or afterglow? (or both...). Is it the high energy tail of the synchrotron flux or it marks the emergence of the SSC process?

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