IL NUOVO CIMENTO Vol. 34 C, N. 3 Maggio-Giugno 2011
DOI 10.1393/ncc/i2011-10884-y

Colloquia: Scineghe2010

On the origin of GeV emission in gamma-ray bursts

L. Nava(1), G. Ghisellini(2) and G. Ghirlanda(2)
(1) *SISSA/ISAS - via Bonomea 265, Trieste, Italy*
(2) *INAF-OAB - via Bianchi 46, Merate, Italy*

(ricevuto il 25 Febbraio 2011; pubblicato online il 26 Maggio 2011)

Summary. — We present spectral and temporal analysis of the Fermi-LAT data for 11 gamma-ray bursts detected in the 100 MeV–100 GeV energy range. This analysis reveals that some features are common to all bursts, both in the spectral and temporal domain. In particular, i) spectra are consistent with $F(E)$ proportional to E^{-1} and do not much evolve in time and ii) the light curves decay in times as $t^{-1.5}$ and, at least in the 50% of cases, present an initial peak. Supported by our results, we suggest that the flux above 100 MeV has the same origin as the afterglow emission detected in the X-ray and in the optical and radio bands. We then interpret it as forward shock emission produced by a radiative fireball expanding in the external environment.

PACS `98.70.Rz` – γ-ray sources; γ-ray bursts.

1. – Introduction

Very high energy ($> 100\,\mathrm{MeV}$) emission in Gamma-Ray Bursts (GRBs) was first detected, in a handful of cases, by the EGRET instrument onboard the CGRO satellite. The Fermi mission is now collecting new exciting results on the GRB emission properties in the MeV–GeV energy range, which has been unexplored since the times of EGRET. The Large Area Telescope (LAT, 40 MeV–300 GeV, [1]) onboard Fermi detected 20 GRBs (18 long and 2 short) above 100 MeV up to November 2010. Thanks to its much better sensitivity and reduced dead time as compared to EGRET, it is now possible, for the first time, to investigate the temporal and spectral properties of this emission and probe its origin.

Several interpretations have been proposed, none of which seems conclusive. The high-energy emission may be associated to the prompt (*e.g.*, inverse Compton on the synchrotron photons produced at internal shocks—synchrotron self-Compton model [2]) or to the afterglow (either synchrotron or synchrotron self-Compton at external shocks [3-5]). Within the models that support an external origin, also the hadronic afterglow model has been proposed, where the simple electron-synchrotron blast wave model is extended by considering ion acceleration and radiation [6].

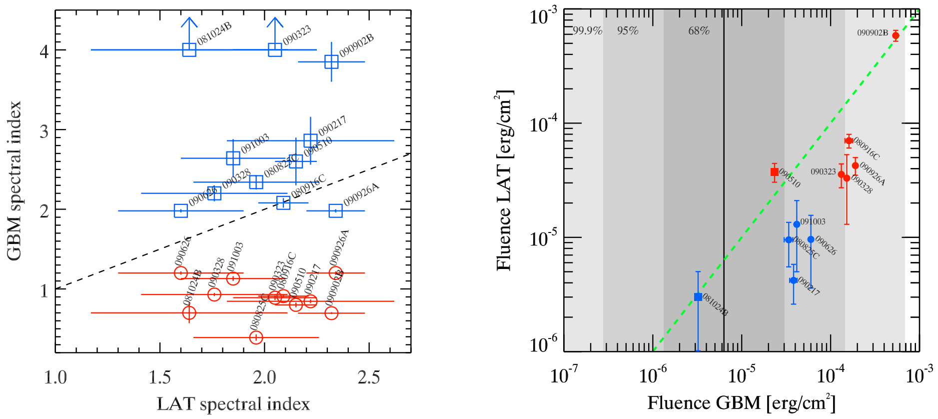

Fig. 1. – Left: LAT spectral index *vs.* GBM low-energy spectral index (circles) and GBM high-energy spectral index (squares). Right: fluence detected by the LAT *vs.* the fluence detected by the GBM, both for long (circles) and short (squares) bursts. Events with fluence larger than 2×10^{-5} erg/cm^2 coincide with GRBs with known redshift. From [7].

The emission above 100 MeV starts during the usual prompt emission detected by the GBM instrument in the 8 keV–30 MeV energy range (often a small delay of seconds or less can be determined) and typically has a longer duration (up to several hundreds of seconds). The spectra are often inconsistent with the extrapolation of the GBM spectra at higher energies (except two cases). These ingredients strongly suggest that the emission above 100 MeV is not just the high energy part of the prompt emission (peaking in the hard X-rays) but it is a different spectral component.

Ghisellini *et al.* [7] analyze the data of 11 GRBs detected by the LAT above 100 MeV. This analysis reveals that some properties are common to all bursts, both in the temporal and spectral domain. On the basis of these results, we propose a theoretical interpretation to explain the origin of this emission.

2. – Spectral properties

All the LAT spectra can be properly modeled with a power-law function. The values of the spectral indices above 100 MeV are shown in fig. 1 (left panel), where they are compared to the low-energy and high-energy spectral indices from the analysis of GBM data. In all but two cases, the LAT emission is not consistent with the extension of the high-energy part of the sub-MeV emission. LAT spectral indices are clustered around $\Gamma \sim 2$, which means that typically the spectrum is $F(E) \propto E^{-1}$. For the brightest bursts it is also possible to perform the time-resolved temporal analysis which reveals that the LAT emission is not affected by strong spectral evolution [7].

In fig. 1 (right panel), the fluence in the LAT energy range (0.1–100 GeV) is compared to the fluence collected by the GBM (8 keV–10 MeV). The shaded areas indicate the 1-2-3σ values of the fluence distribution of long GRBs detected by the GBM. GRBs with LAT emission have, therefore, a fluence (in the keV–MeV range) larger than the average. The most extreme fluences ($> 2 \times 10^{-5}$ erg/cm^2) are reached by GRBs with known redshift. In some cases, the fluence values may differ from those reported by the

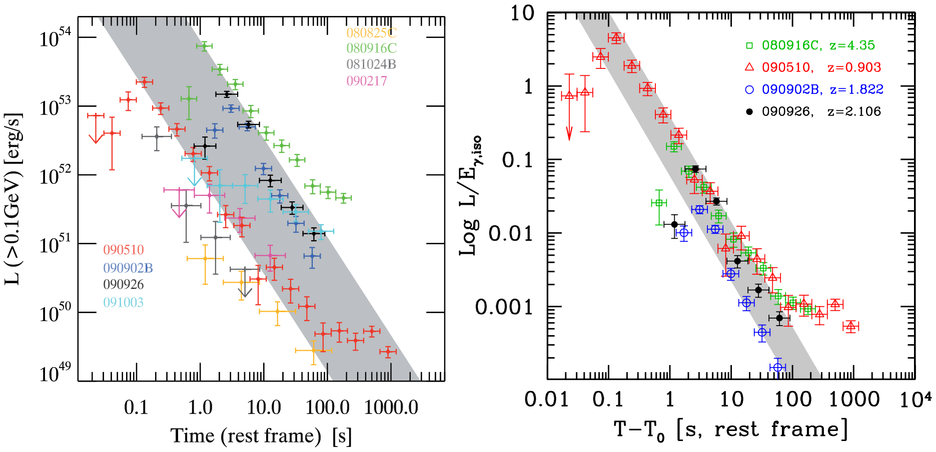

Fig. 2. – Left panel: light curves (0.1–100 GeV) of the 8 brightest GRBs. For GRBs without measured redshifts we assumed $z = 1$ for short and $z = 2$ for long events. Right panel: light curves of the 4 brightest GRBs with redshift, normalized to the total energetics in the GBM energy range. Upper limits are at 2σ level. The grey stripes indicate a slope $t^{-10/7}$. From [7].

LAT Collaboration [8]. Note, however, that their fluence energy ranges are different from those chosen by us. For GRB 081024B the comparison between our results and those reported by the LAT Collaboration is difficult since they report different values (both for the GBM and the LAT fluences) in two different papers ([8] and [9]).

3. – Temporal properties

All the analyzed bursts show similar temporal properties of their emission above 100 MeV. The light curves (that last longer than the emission detected by the GBM) are characterized by a peak, after which the flux decays as a power law. For the brightest bursts (fig. 2) we found that the high-energy flux decays in time as $t^{-1.5}$. An initial rise (compatible with t^2) is also seen. The right panel of fig. 2 shows the light curves of the 4 brightest GRBs with redshift, once the 0.1–100 GeV luminosity is divided by the energetics of the flux detected by the GBM. The shaded stripe has a slope $t^{-10/7}$ and it is shown for comparison. These four GRBs show a common behaviour, being all consistent, within the errors, with the same decay, both in slope and in normalisation. Note that GRB 090510, a short burst, behaves similarly to the other 3 bursts, that belong to the long class, but its light curve begins much earlier. The light curves in fig. 2 are not background subtracted. When the LAT flux is high the background contamination is negligible. At later times, instead, the background contribution may be important and may produce a plateau.

4. – Interpretation

The spectral and temporal characteristics are the same as observed/predicted by the synchrotron external shock scenario giving rise to the afterglow. We therefore suggest that the high-energy emission of the GRBs detected by LAT is forward emission produced by relativistic shocks on the external medium [7]. If this is the case, from the peak time of the LAT flux it is possible to estimate the initial bulk Lorentz factor of the fireball Γ_0. For the 4 brightest GRBs we estimate a Lorentz factor $\Gamma_0 > 1000$. This is nothing unexpected: faster fireballs should decelerate earlier and produce a brighter afterglow mostly at high frequencies. Indeed, in Fermi/LAT bursts, the GeV emission could be the tracer of the fastest fireballs (*i.e.* we are starting to explore the high value tail of the Γ_0 distribution), thus explaining the relatively low fraction (10%) of Fermi bursts with GeV emission. Our picture easily explains i) the delay between the start of the LAT emission with respect to the start of the GBM emission, ii) its longer duration, iii) the presence of a peak in the light curve and iv) the smoothness of the temporal behavior. Some additional ingredient must be taken into account to properly model the high-energy light curve. The flat $\nu F(\nu)$ spectrum in the GeV band (fig. 1) suggests that we are observing close to its spectral peak. This means that the flux detected by the LAT instrument is a good estimate of the bolometric flux. The steep temporal decay common to all GeV light curves then requires a radiative regime instead of the standard adiabatic one (which predicts a bolometric flux proportional to t^{-1}). With respect to the usual adiabatic fireball case, in a radiative fireball a considerable fraction of the dissipated energy is given to electrons and pairs and efficiently radiated. The radiative regime explains both the steep decay of the GeV light curve, both the low flux level of the standard X-ray and optical afterglow. In fact, the high radiation efficiency with respect to the adiabatic case produces a bulk Lorentz factor decreasing more rapidly [10]. A steep flux decay is then observed, the energy content of the fireball decreases fast and, at later times, when data are available in X-rays and in the optical, the afterglow appears less energetic. A radiative regime can be established if the circumburst medium is enriched by pairs. In [7], we considered a model to explain how the prompt radiation photons can enrich the interstellar medium of pairs, just before the arrival of the shock produced by expanding fireball on the external medium, proposed by [11].

Our theoretical interpretation of the high-energy emission must be consistent with afterglow observations in the X-ray and optical regimes. The new results of Fermi together with the observations at other wavelengths from space (Swift) and from ground do represent a unique opportunity to test this picture, which must be able to explain under the very same consistent model the emission from the GeV to the X-ray/optical and radio bands.

REFERENCES

[1] Atwood W. B., Abdo A. A., Ackermann M., *et al.*, *Astrophys. J.*, **697** (2009) 1071.
[2] Abdo A. A. *et al.*, *Nature*, **462** (2009) 331.
[3] Kumar P. and Barniol Duran R., *Mon. Not. R. Astron. Soc.*, **409** (2010) 226.
[4] Gao W. H., Mao J. R., Xu D. and Fan Y. Z., *Astrophys. J.*, **706** (2009) 33.
[5] De Pasquale M., Schady P., Kuin N. P. M. *et al.*, *Astrophys. J.*, **709** (2010) 146.
[6] Razzaque S., Dermer C. D. and Finke J. D., *Open Astron. J.*, **3** (2010) 150.
[7] Ghisellini G., Ghirlanda G., Nava L. and Celotti A., *Mon. Not. R. Astron. Soc.*, **403** (2010) 926.
[8] Abdo A. A. *et al.*, *Astrophys. J.*, **712** (2010) 588.
[9] Abdo A. A. *et al.*, *Science*, **323** (2009) 1688.
[10] Sari R., Piran T. and Narayan R., *Astrophys. J.*, **497** (1998) 17.
[11] Beloborodov A. M., *Astrophys. J.*, **565** (2002) 808.