FERMI OBSERVATIONS OF THE JET PHOTOSPHERE IN GAMMA RAY BURSTS

ELENA MORETTI
on behalf of the Femi LAT collaboration
Oskar Klein Center, Department of Physics, Stockholm University, 106 91 Stockholm, Sweden and Department of Physics, KTH Royal Institute of Technology, 106 91 Stockholm, Sweden

Fermi Gamma Ray Space Telescope observations of the prompt emission in gamma-ray bursts have shown that several components can be present in the spectrum. The physical source for one such feature is likely emission from a jet photosphere. The detailed *Fermi* observations regarding the behaviour of the photosphere show that it plays a significant role in the formation of the spectrum in several strong bursts. In particular, the identification of the photospheric component is important in order to correctly interpret the emission. Moreover the observations of the thermal spectra broadening in one of the *Fermi* bursts support the models of geometrical and physical processes that can broaden the photospheric spectrum from a relativistic outflow. These same processes can therefore explain the non-thermal spectra seen in many bursts.

1 Introduction

Gamma ray bursts (GRBs) are cosmological flashes whose prompt emission, lasting for 0.01-100s, is in the gamma ray band. Their late emission lasting for thousands of seconds, can be detected at lower energy ranges like optical and radio. One or two GRBs per day are typically observed, but their origin and the particle acceleration mechanisms involved still remain unknown. The favourite hypothesis on their origin is the collapse of a supermassive star, while there is no leading hypothesis for the acceleration mechanisms involved in the outflow responsible for the prompt emission.

In the fireball model the gravitational potential energy of the core collapse of a supermassive star can be extracted in a short timescale to form an unstable relativistic outflow with a bulk Lorentz factor $\Gamma \sim 100$ to 1000. Thc initial gravitational energy can be transformed into kinetic energy (e.g. Mészáros & Rees 1993 [13]) of the plasma that further creates the jet emerging from the star envelope. As the initial fireball cools and becomes transparent, thermal, photospheric emission is expected to be emitted. Furthermore, these outflows naturally lead to dissipation processes, such as shocks or magnetic reconnection. The dissipated energy accelerates leptons to high energies, and these then radiate synchrotron and inverse Compton radiation. The process of conversion of the internal or kinetic energy of the shells, which is carried mainly by protons (and/or the magnetic field), to the electrons which are the radiating agents, is most uncertain. This emission constitutes the prompt phase radiation, a flash of gamma-rays lasting from a fraction of a second to a few minutes.

Since their discovery about 40 years ago many missions have been dedicated to the GRBs and in particular to understand the emission mechanisms involved in the prompt emission phase, but not yet a clear unique picture has emerged from the observations. The spectrum of the prompt is commonly thought to be non-thermal and modeled with a form function proposed by Band et al. 1993 [4] consisting of two power laws smoothly joint together. In some cases this function has found to be in agreement with the spectrum produced by synchrotron emission from an electron population in fast cooling regime whose energy distribution is a power law (e.g. Tavani 1996 [22]). On the contrary most of the observed spectra fitted with the Band function have a low energy index (commonly called α) steeper than thc slopes allowed by the optically-thin synchrotron or synchrotron self-Compton model predictions. Moreover the outflow internal shocks that produce the synchrotron emission are demonstrated to be too inefficient to provide the observed energy release and the correlation between the peak energy and the luminosity (Ramirez-Ruiz & Lloyd-Ronning 2002 [18]). On the other hand the original fireball model of gamma-ray bursts predicts a strong photospheric component during the prompt phase (Goodman 1986 [8], Paczyński 1986 [16]). The very high optical depth to scattering expected near the base of the flow implies that, regardless of the exact nature of the emission process, the resulting spectrum thermalises and is observed as a Planck spectrum. In this same frame also a possible softening of the low energy spectral index, due to geometrical effects, has been proposed (Paczyński 1986 [16]).

An hybrid model has been proposed by Mészáros & Rees 2000[14] where an dditional optically-thick thermal (blackbody) component that may contribute to the observed non-thermal spectrum. The observed spectrum and its evolution would be the result of super imposed emissions coming from two different emission regions of the outflow. This model explains not only the hard spectral slopes but also the observed spectral correlation between peak energy and luminosity and therefore the high radiative efficiency required to produce such spectra.

2 The BATSE Era

The photospheric component was first seen in the BATSE data covering the 25-2000 keV energy range. Several GRB spectra could be equally well or better described by a Plank function together with a power law component respect to the commonly used Band function[19]. The evolution of the thermal component throughout the duration of the burst was observed to have a common behaviour in the studied bursts. The black body temperature evolution follows a broken power law while the normalization of the Plank component follows a power law. As can be seen in fig.1 the normalization parameter increases with time, while the temperature parameter decreases down to an undetectable level.

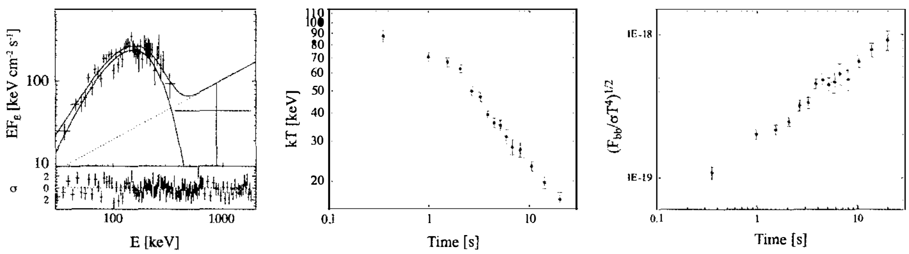

Figure 1: Example of a BATSE detected burst spectrum compatible with photospheric emission (left). The temperature (centre) and the normalization (right) evolutions show the typical behaviour of this type of bursts.

3 The *Fermi* Era

The *Fermi* telescope, launched in May 2008, has a larger energy coverage for the GRB than BASTE. The two experiments onboard *Fermi*, namely the Gamma ray Burst Monitor (GBM [12]) and the Large Area Telescope (LAT [2]), provide an uninterrupted detection energy range from 8 keV to 200 GeV. Many new GRB proprieties have been discovered by the *Fermi* team in these years, like the delay onset of emission > 100 MeV or the presence of a spectral extra component that accounts for the high energy emission in some GRBs. The thermal component already seen in the BATSE bursts is confirmed by the *Fermi* observations and the wider energy covcrage allows to further investigate the higher energy part of the spectra modeled by a power law in the BATSE data.

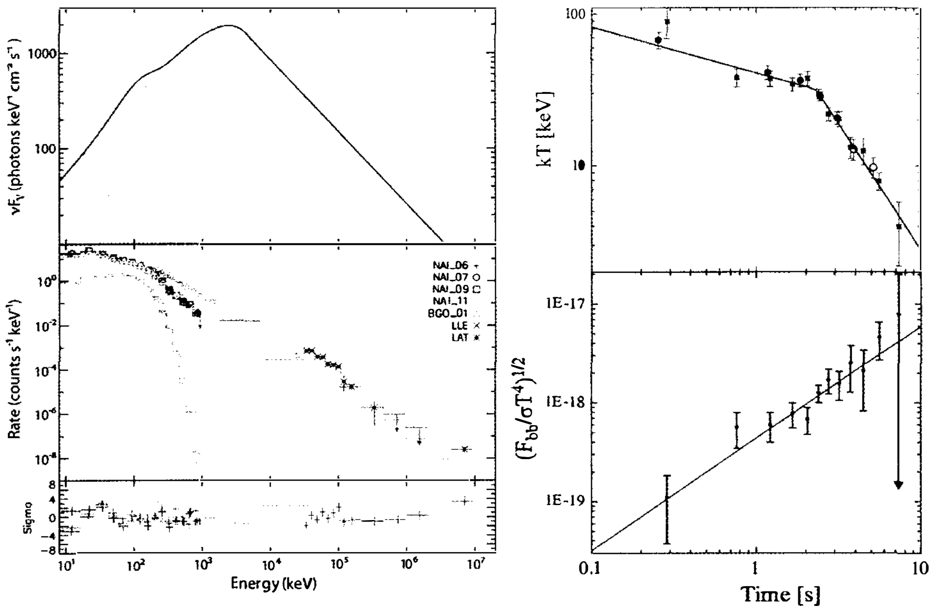

Figure 2: Time-integrated spectrum of GRB110721A fitted with a Band function combined with a Planck function (left). The upper panel shows the model spectrum in $\nu F \nu$ representation, the middle panel the count spectrum and the lower panel the residuals of the fit. The temporal evolution of the black body temperature is shown in the top right panel and the evolution of its normalization in the bottom right panel. In the top panel, filled circles indicate a $> 5\sigma$ significance of the blackbody, open circles a 3σ significance. The smaller points in both panels are from fits using a high time resolution, which lowers the significance of the component.

3.1 The double-humped spectrum

The cases of GRB090820A (Burgess et al.[6]) and GRB100924B (Guiriec et al.[9]) proposed a "double humped" spectrum where together with the Plank function there is an additional spectral component that peaks at higher energy and is generally shaped like a Band function up to 10 MeV. This type of GRB has been recently confirmed by the GRB110721A that was detected by the GBM and LAT detectors. In this case Axelsson et al.[3] found that the second component peaks at 15.2 ± 1.3 MeV at the beginning of the burst and declines like a power law with index -1.22 ± 0.13 as a function of time. The temporal evolution of the temperature and the normalization of the Plank function follow the same pattern found in the BATSE bursts: a broken power law and a power law respectively (see fig.2).

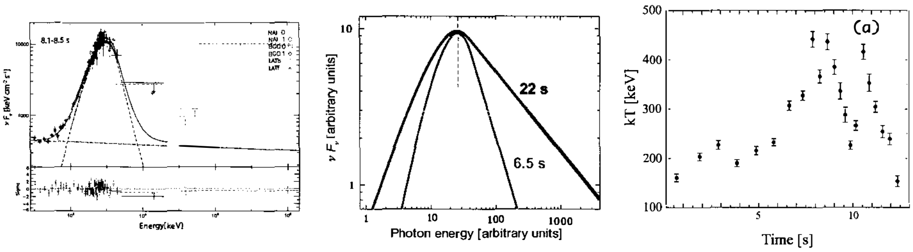

Figure 3: Photospheric emission spectrum of GRB090902B at early time (left pannel). Broadening of the spectrum at later times (center) and temporal evolution of the temperature in the first epoch (right).

3.2 The photospheric dominated spectrum

Among the almost 40 bursts detected by both the GBM and the LAT detectors, some exhibit the double humped spectral behaviour while others do not. In particular GRB090902B shows a dominant photospheric component but no Band-like one. The high energy emission seen in this bursts is well described from Abdo et al.[1] by a power law that extends throughout all the spectrum from 8 keV.

A further study of this burst from Ryde et al.[20] with finer resolved time bins divides the emission in two epochs: from 0.0s to 12.5s and from 12.5s to 25s. In the first epoch the spectral photospheric component is very narrow, $\alpha \sim 0.3$ and $\beta \sim -4$ (see fig. 3 first panel). The measured value of α has been demonstrated by Ryde et al.[21] to be highly incompatible with the typical $\alpha = -1.5$ in thc casc of synchrotron emission from fast cooling electrons in a optically thin region. The second epoch instead is characterised by a broadening of the peaked emission towards a spectral shape that more resembles the commonly seen wide spectra (see fig. 3 middle panel).

The identification of the clear photospheric component in the early time bins provides the opportunity to follow thc evolution of the physical conditions of the outflow, in particular the radius of the photosphere and the bulk Lorentz factor that seem to increase at later times. In this case the temporal evolution of the black body temperature (see fig. 3 last panel) is not described by a broken power law as seen in the double humped spectra, suggesting different environmental conditions at the emission site.

4 Modification of the Plank function in photospheric emission

GRB090902B gave a solid observational contribution to the debate of the spectral shape of the photospheric emission. The possible modification of the Plank function under particular emission conditions or geometrical effects was already hypothesized to explain Band-like spectra.

In the case of subphotospheric emission several different mechanisms for the energy dissipation below the photosphere can intervene to modify the original Plank function. Among those magnetic reconnection (Giannios 2008 [7]), internal shocks (Ioka 2010 [10]) or collisional dissipation (Beloborodov 2010 [5]). Or if the amount of dissipation and parameters of the outflow are varied, it is possible to produce a wide range of spectral shapes by such subphotospheric energy release (Peer et al. 2006 [17], Nymark et al. 2011 [15]) more complex than the pure Band function.

Purely geometrical effects can also broaden the spectrum by making the α value range between -1 and 0.4 as shown by Lundman et al.[11]. They use a combination of analytical modeling and numerical simulations to describe the energy spectra of the GRB outflow as a function of the viewing angle in the case of a narrow jet. In the case of a wider jet the spectral broadening is present only if the viewing angle is close to the jet opening angle.

5 Summary

The advent of the *Fermi* telescope brought a deeper understanding of the GRB spectra. Important results, already outlined by the BATSE data, on the emission processes involved in the outflow have been confirmed and expanded. A recurring double humped spectral shape in the *Fermi* GRBs is suggesting that the presence of the photospheric emission is more common than previously thought. By connecting the Plank function component to the jet photosphere we can study the radius of the photosphere and the bulk Lorenz factor of the emitting region. Furthermore the identification of the main spectral component of GRB090902B with the emission from the photosphere allows the study of the broadening of the Plank function. Several mechanisms can account for this modification of the Plank function from dissipative processes to geometrical effect of the jet viewing angle. Including a photospheric component is thus a first step to understanding the physical origin of GRB prompt emission - something which the Band function cannot provide.

Acknowledgments

The *Fermi* LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operations phase is also gratefully acknowledged.

References

1. A. A. Abdo *et al*, *The Astrophysical Journal* **706**, L138 (2009).
2. W. B. Atwood *et al*, *The Astrophysical Journal* **697**, 1071 (2009).
3. M. Axelsson *et al*, *The Astrophysical Journal* **757**, L31 (2012).
4. D. Band, *et al*, *The Astrophysical Journal Letters* **413**, 281 (1993)
5. A. Beloborodov, MNRAS **407**, 1033 (2010).
6. J. M. Burgess *et al*, *The Astrophysical Journal* **741**, 24 (2011).
7. D. Giannios, A&A **480,** 305(2008).
8. P. Goodman, *The Astrophysical Journal* **308**, L47 (1986)
9. S. Guiriec *et al*, *The Astrophysical Journal* **727**, 33 (2011).
10. K. Ioka, *Progress of Theoretical Physics* **124,** 667(2010).
11. C. Lundman, A. Peer, & F. Ryde, MNRAS **428**, 2430 (2013).
12. C. Meegan *et al*, *The Astrophysical Journal* **702**, 791 (2009).
13. P. Mészáros, and M. J. Rees, *The Astrophysical Journal* **530**, 292 (1993)
14. P. Mészáros, and M. J. Rees, *The Astrophysical Journal* **530**, 292 (2000)
15. T. Nymark *et al*, *arXiv:1111.0308,* (2011).
16. B. Paczyński, *The Astrophysical Journal Letters* **308**, L47 (1986)
17. A. Peer, P. Mészáros, & M. J. Rees, *The Astrophysical Journal* **642**, 995 (2006).
18. E. Ramirez-Ruiz, & N. M. Lloyd-Ronning *New Astronomy*, **7**, 197, (2002).
19. F. Ryde, *The Astrophysical Journal* **614**, 827 (2004).
20. F. Ryde *et al*,. *The Astrophysical Journal Letters* **709**, L172 (2010).
21. F. Ryde *et al*, MNRAS **415**, 3693 (2011).
22. M. Tavani, *The Astrophysical Journal* **466**, 768 (1996)