Numerical simulations of the photospheric emission in long-duration gamma-ray bursts

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Photospheric emission is an unavoidable component of the prompt emission of gamma-ray bursts. Its magnitude and spectral shape are, however, uncertain and depend on jet properties such as its magnetization and the dissipation mechanism and location. Some models call for a dominant role of photospheric emission in the prompt spectrum, while others only contain a small photospheric contribution. We present a review of numerical results on the properties of the photospheric emission in long-duration gamma-ray bursts, discussing the role of the photospheric component in the explanation of ensemble correlations and the origin of its non-thermal appearance.

Keywords: Gamma-rays: bursts; relativistic outflows.

1. Introduction

The origin of the prompt emission spectrum of gamma-ray bursts (GRBs) is still a matter of open debate, despite several decades of intense study. While many models have been proposed, the two that gather most consensus are synchrotron in a magnetized outflow[5,7,22,26,27] and photospheric radiation[12,14,20,21,23].

Both models are successful at explaining some burst features, but face problems in explaining others. For example, synchrotron can naturally explain the non-thermal broad-band nature of the spectrum, but faces challenges in accounting for the ensemble correlations, such as the Amati[1], Golenetskii[25], and luminosity-Lorentz factor[8] correlations. On the other hand, while photospheric radiation can naturally explain the ensemble correlations[16–18], it faces serious challenges in accounting for the broad band nature of the spectrum. While Comptonization models can reproduce, at least in part, the high-frequency power-law spectra[2,6,9,15,21], populating the lower frequencies with extra photons on top of the predicted black-body shape has proven quite challenging[6,24].

One clear advantage of photospheric radiation with respect to the internal shock synchrotron model is that it is amenable to implementation in numerical codes, so that the radiation properties can be predicted directly from numerical simulations of

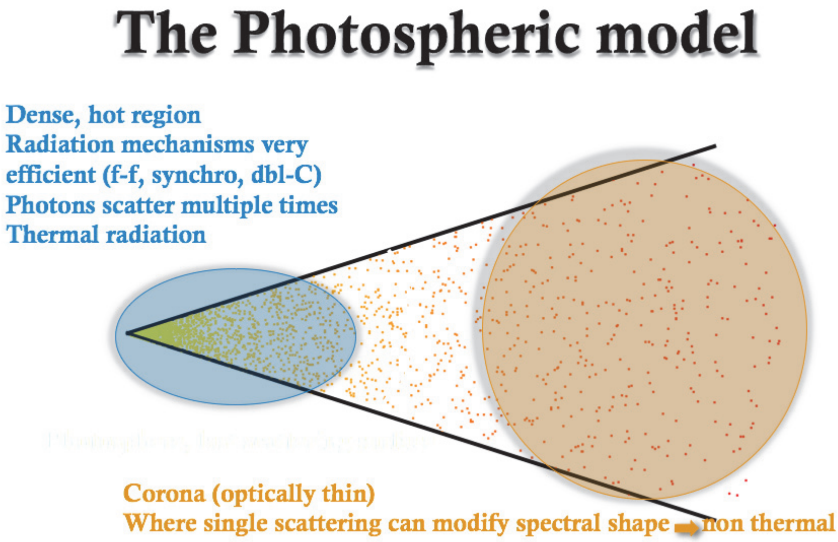

Fig. 1. Cartoon explaining the general features of the photospheric model. At small radii the jet is hot and dense, so that matter and radiation are strongly coupled. Radiation mechanisms, such as free-fre emission, synchrotron, and double Compton scattering (f-f, synchro, dbl-C) are efficient. As the jet expands, the coupling decreases until it is lost at the photosphere. Beyond the photosphere the radiation leaks out of the jet. The spectral shape can be modified by dissipation in the trans-photospheric region, but the spectral peak is unaffected.

GRB jets[13,14,16–19] relaxing the one emission zone approximation customarily made in synchrotron studies. In this paper we review recent results of numerical studies of the photospheric emission in long duration GRBs, focusing on ensemble properties such as the Amati[1], Golenetskii[11], and Luminosity-Lorentz-factor[8] correlations.

2. The Photospheric Model

Figure 1 shows a pictorial description of the photospheric model. The model is based on the consideration that at the base of the jet and during its early expansion matter and radiation are coupled. The continuous energy exchange between the radiation field and the leptonic component of the jet is very efficient and matter and radiation are in equilibrium. Under such conditions, the radiation is known to assume a black-body spectrum (Planck spectrum in a non-accelerating outflow). The coupling is efficient out to a certain radius, at which the radiation and matter decouple. In first approximation the radiation spectrum can be assumed to be in equilibrium out to such radius and completely decoupled afterwards[14,19]. While energy dissipation in the trans-photospheric region ($0.1 < \tau_T < 10$) can modify the spectral shape, adding non-thermal tails to the spectrum, energy consideration suggest that they should not modify the peak frequency of the emission[14,16]. For this reason, until recently, numerical simulations of the prompt emission were used

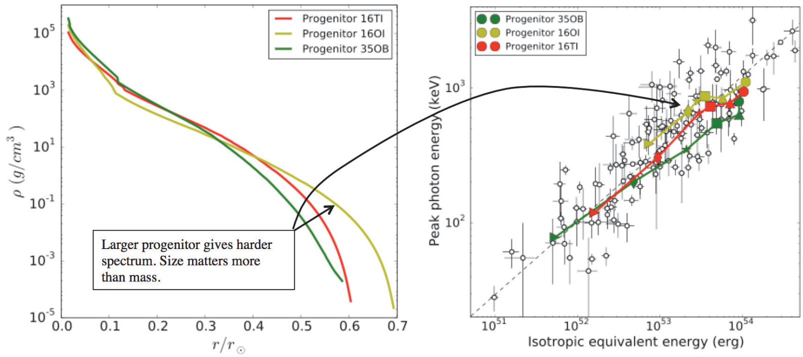

Fig. 2. The Amati correlation as explained within the photospheric scenario. In the right panel, GRB spectral data are compared to the peak frequency predicted by hydrodynamic numerical simulations of long GRB jets[17]. Different colors show observations of similar jets propagating through different progenitor stars (left panel).

mainly to compare between the peak frequency of samples of observed bursts and results of the simulations. Such comparisons are described in the section below.

3. Results

Figure 2 shows a sample result from a set of numerical simulations of long-duration gamma-ray burst jets. Jets are injected in the core of a massive progenitor star with a flat-top energy distribution within a certain opening angle. The jet propagation is computed, and its interaction with the progenitor star increases dissipation, and creates a polar structure due to shear motions. The jet spine moves faster, has a higher temperature, and a higher luminosity. As a consequence, different observers see different bursts, and the Amati correlation can be explained as a result of similar stellar explosions seen by observers in different directions. Changing jet parameters or stellar progenitor parameters only affects the observed properties of the bursts in a minor way, shifting the sequence in the Amati correlation but not creating any inconsistency[17] (right panel of Figure 2). Analogous results have been obtained for the Golenetskii correlation[18] which is a more robust correlation not affected by selection effects and for the correlation between the outflow velocity and its energy[17].

One problem of the results described above is the uncertainty in the radius at which the spectrum is released, i.e. the radius at which the interaction between matter and radiation ceases. Early results based on spectrum decoupling at $\tau_T = 1$ yielded a quantitative disagreement between simulations results and observations[14,16,19]. It was subsequently understood that the decoupling happens at higher optical depths due to the inefficiency of the exchange of energy via Compton scattering[10]. Correcting for that yielded quantitative agreement[17] (see Figure 2).

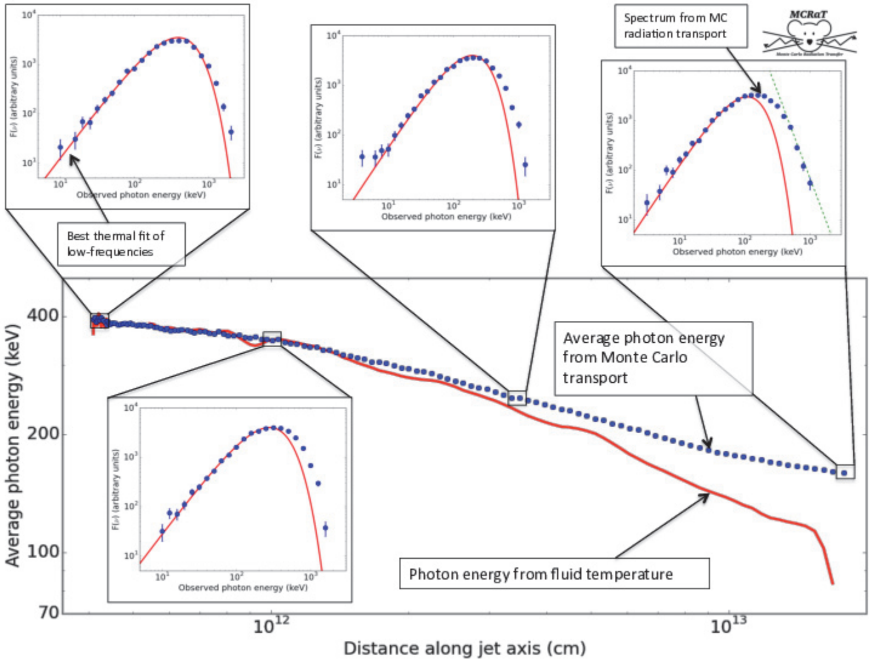

Fig. 3. Evolution of the average photon frequency as a function of radius in a long GRB simulation (main panel, simulation from [14]). The red line shows the result under complete matter-radiation coupling, while the blue symbols show the result of MCRaT, a Monte Carlo Radiation Transfer code (Lazzati in preparation). As predicted [10] radiation and matter decouple well inside the photosphere ($\tau_T = 1$ is located at the far right, where the red line drops suddenly). However, the two fluids keep interacting and only eventually evolve completely independently beyond the photosphere. The inset show spectra at various distances, showing the development of a non-thermal high-frequency tail.

3.1. *Spectra*

In order to relax the assumption of sudden decoupling on which previous results have been based, Monte Carlo radiation transfer codes have been recently developed. These codes are also based on the assumption that, at some point deep in the outflow, matter and radiation are in equilibrium. The photons, however, are individually injected and their propagation followed exactly under the assumption that interactions are purely via Compton scattering and that there is no emission or absorption of radiation [13] (Lazzati in preparation). Such codes can therefore not only predict the frequency of the peak of the radiation spectrum, but also compute the overall spectral shape.

Figure 3 shows the evolution with radius of the average photon energy both under the assumption of complete coupling (red line) and obtained by the Monte Carlo

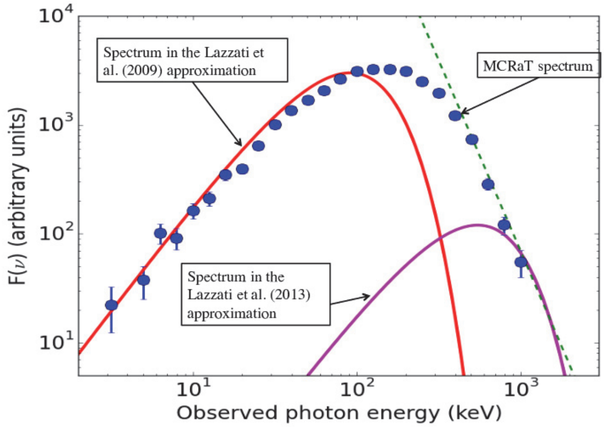

Fig. 4. Synthetic spectrum of a GRB outflow as predicted by MCRaT (blue symbols). Solid lines show how it compares to the spectra predicted under earlier approximation of sudden decoupling (Lazzati in preparation).

Radiation Transfer code MCRaT. While the two curves agree deep in the flow (left of the figure), the two lines diverge well within the photosphere (as predicted[3,4,10]) but radiation and matter remain weakly coupled until they reach the photosphere[3]. In this interval of radii, the spectrum builds a high-frequency tail of non-thermal appearance (see Figure 4) that can explain the observations. On the low-frequency side, however, the thermal nature of the photospheric spectrum is hardly modified and stronger dissipation, like the one seen in precessing jets, needs to be invoked[13].

4. Discussion

Even though radiation transfer studies of the formation of the prompt emission in GRBs are still in their infancy[13] (Lazzati in preparation), they show promise. The photospheric scenario is now in its full maturity, in which prediction can be made with very few approximations and considering the multi-region origin of the photons. Still, photospheric radiation faces serious challenges in explaining the non-thermal low-frequency nature of the GRB spectra, and additional components, such as a mild synchrotron emission, are likely needed to explain the GRB prompt spectrum in its entirety.

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References

1. Amati, L., et al., *Astronomy & Astrophysics*, **390**, 81 (2002)
2. Beloborodov, A. M., *MNRAS*, **407**, 1033 (2010)
3. Beloborodov, A. M., *The Astrophysical Journal*, **737**, 68 (2011)
4. Beloborodov, A. M., *The Astrophysical Journal*, **777**, 114 (2013)
5. Bosnjak, Z., Daigne, F., Dubus, G., *Astronomy & Astrophysics*, **498**, 677 (2009)
6. Chhotray, A., & Lazzati, D., *The Astrophysical Journal*, **802**, 132 (2015)
7. Daigne, F., Mochkovitch, R., *MNRAS*, **296**, 275 (1998)
8. Ghirlanda, G., et al., *MNRAS*, **420**, 483 (2012)
9. Giannios, D., *Astronomy and Astrophysics*, **457**, 763 (2006)
10. Giannios, D., *MNRAS*, **422**, 3092 (2012)
11. Golenetskii, S. V., Mazets, E. P., Aptekar, R. L., & Ilinskii, V. N., *Nature*, **306**, 451 (1983)
12. Goodman, J., *The Astrophysical Journal*, **308**, L47 (1986)
13. Ito, H., Matsumoto, J., Nagataki, S., Warren, D. C., & Barkov, M. V., *The Astrophysical Journal*, **814**, L29 (2015)
14. Lazzati, D., Morsony, B., Begelman, M. C., *The Astrophysical Journal*, **700**, L47 (2009)
15. Lazzati, D., & Begelman, M. C. 2010, *The Astrophysical Journal*, **725**, 1137 (2010)
16. Lazzati, D., Morsony, B., Begelman, M. C., *The Astrophysical Journal*, **732**, 34 (2011)
17. Lazzati, D., Morsony, B., Margutti, R., Begelman, M. C., *The Astrophysical Journal*, **765**, 103 (2013)
18. López-Cámara, D., Morsony, B. J., & Lazzati, D., *MNRAS*, **442**, 2202 (2014)
19. Mizuta, A., Nagataki, S., & Aoi, J., *The Astrophysical Journal*, **732**, 26 (2011)
20. Pe'er, A., Mészáros, P., Rees, M. J., *The Astrophysical Journal*, **635**, 476 (2005)
21. Pe'er, A., Mészáros, P., Rees, M. J., *The Astrophysical Journal*, **642**, 995 (2006)
22. Rees, M. J., Mészáros, P., *The Astrophysical Journal*, **430**, L93 (1994)
23. Rees, M. J., Mészáros, P., *The Astrophysical Journal*, **628**, 847 (2005)
24. Vurm, I., Lyubarsky, Y., & Piran, T., *The Astrophysical Journal*, **764**, 143 (2013)
25. Yonetoku, D., Murakami, T., Nakamura, T., Yamazaki, R., Inoue, A. K., Ioka, K., *The Astrophysical Journal*, **609**, 935 (2004)
26. Zhang, B., Yan, H., *The Astrophysical Journal*, **726**, 90 (2011)
27. Zhang, B., Zhang, B., *The Astrophysical Journal*, **782**, 92 (2014)