Varying Faces of Photospheric Emission in Gamma-ray Bursts

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Among the more than 1000 gamma-ray bursts observed by the Fermi Gamma-ray Space Telescope, a large fraction show narrow and hard spectra inconsistent with non-thermal emission, signifying optically thick emission from the photosphere. However, only a few of these bursts have spectra consistent with a pure Planck function. We will discuss the observational features of photospheric emission in these GRBs as well as in the ones showing multi-component spectra. We interpret the observations in light of models of subphotospheric dissipation, geometrical broadening and multi-zone emission, and show what we can learn about the dissipation mechanism and properties of GRB jets.

1. INTRODUCTION

Despite having been studied for well over 20 years, the emission mechanisms active during the prompt phase in gamma-ray bursts (GRBs) remain unclear. A robust prediction of the fireball model for GRBs [1, 2] is that the relativistic jet is initially opaque and therefore photospheric emission is inevitable. Yet its strength is uncertain and it is therefore not necessarily detectable. In 1986, both Paczynski [3] and Goodman [4] suggested a strong contribution of photospheric emission in GRB spectra; however, the observed spectra generally appear nonthermal and these models were therefore not considered viable.

Interest in the photospheric component resumed with observations of GRBs using Compton Gamma-Ray Observatory/BATSE (20–2000 keV). Ryde [5] found that in many individual emission pulses an equally good or better fit could be found by using a model comprising a Planck function and a power-law, as compared to the traditional Band function. Additionally, it was found that the evolution of the Planck function component during the prompt phase followed well defined and consistent characteristics. The Planck component was interpreted as the photosphere of the GRB. At present there is again mounting evidence from theoretical considerations that the photosphere of the relativistic outflow (jet) plays an important role [6–9].

In this paper the observational signs so far attributed to photospheric emission will be discussed and interpreted in light of models of subphotospheric dissipation, geometrical broadening and multi-zone emission. Photospheric emission can give rise to many different spectral shapes, and pure blackbody emission is rarely expected.

2. OBSERVATIONS

As noted above, predictions of photospheric emission came early in the study of GRBs. Yet it was not until the detailed spectral studies made possible by CGRO/BATSE that the first clear observational signs were seen. In part this may be due to the ambiguity in attributing spectral components to distinct physical processes. This has to some extent meant that the search for photospheric emission has become a search for blackbody (or Planckian) components in the spectrum: while the photosphere can in principle give rise to many different shapes, a blackbody can only come from the photosphere.

2.1. Blackbody-like spectra

Ghirlanda et al. [10] first reported the presence of a blackbody component in the initial phase of some GRBs detected with CGRO/BATSE. Ryde [5] also showed that some GRBs could be well fit with single Planck functions throughout the prompt phase. However, such cases are extremely rare. In the entire BATSE catalogue, only 6 out of ~ 2200 GRBs are well described by a pure blackbody. The situation is similar for the Fermi catalogue: only 2 such bursts in over 1400 have reported [11, 12].

Although these numbers may seem low, what is perhaps more surprising is that there are such cases at all. Already from the start, it was shown that purely geometrical considerations meant that photospheric emission should be somewhat broader than a single temperature Planck function. The fact that there are such narrow spectra is thus very constraining for theoretical models.

An interesting case for the study of photospheric emission is GRB090902B, one of the brightest bursts seen by Fermi. During the first part of the emission episode, the main spectral peak is very narrow and well-fit by a multicolor blackbody [13]. However, during later times in the pulse the spectrum broadens considerably. As the spectral evolution can be followed, it is clear that the same component is seen throughout the prompt phase. The blackbody-like spectrum at early times ties it to the photosphere, and GRB090902B thus shows that photospheric emission
3. MULTI-COMPONENT SPECTRA

One of the most striking results of the Fermi satellite is the discovery of multiple components in the spectrum of GRBs. Bright bursts, where the signal-to-noise ratio is highest, show statistically significant deviations from a simple Band function [14]. One component commonly found is a power-law extending to high energies (e.g., GRB 080916C). However, a few bursts also show features at lower energies (<100 keV), which are well-fit by a Planck function. Perhaps the strongest such example is GRB110721A, where the significance of the extra component was greater than 5σ [14].

The results found with Fermi match those previously seen in BATSE data. Ryde [5] found that a model comprising a blackbody and a power-law provided a good fit to several GRB spectra observed by BATSE. The power-law index was greater than -2, so it was clear that there had to be a turn-over at higher energies. With the much broader energy range afforded by Fermi, the power-law seen in the BATSE data is revealed as the low-energy slope of the Band component. It should be noted that also Fermi has detected a power-law component in the spectra; however, this feature is seen in addition to the Band component, and the temporal behavior is very different. Its origin is not yet understood, but may be related to the mechanism producing the temporally extended GeV emission [14].

Another feature which strengthens the common origin of the blackbody components in BATSE and Fermi spectra is their temporal evolution. The BATSE components showed a typical behavior where the temperature decayed with time as a broken power-law. This distinctive feature is also seen in the Fermi data.

3.1. Effects of multiple components

The additional blackbody component detected is typically subdominant, in general contributing only 5-10% of the total flux. For this reason, its presence

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Figure 3: Resulting fits when the spectrum from GRB120323 is fit with a pure Band component (top) and an additional blackbody component (bottom). Adding the blackbody component does not give a statistically sufficient improvement to claim its presence. However, the parameters of the Band component are changed when the blackbody component is present, and therefore different interpretations may be allowed. Adapted from Guiriec et al. [16].

As thermal emission is a well-known physical process, identifying such a component allows physical parameters of the outflow to be derived [17]. These include the bulk Lorentz factor, jet-launching radius and saturation radius. For instance, studies of GRB110721A have found that the Lorentz factor was initially around 1000, then decreased throughout the pulse to values \( \sim 200 \) [15]. The jet launching radius was instead found to increase from \( 3 \times 10^6 \) cm to \( 2 \times 10^9 \) cm [18].

4. INTERPRETATIONS

In the case of “typical” single-component GRB spectra, it is generally assumed that a single process is giving rise to the emission. For spectra well-fit by a single or multi-temperature blackbody, the most likely candidate is photospheric emission.

For the multi-component GRBs, the interpretation is less straight-forward. A natural first assumption is to connect the two components to different emission regions. The blackbody component is then attributed to thermal emission arising from the photosphere, and the Band component related with non-thermal radiation further out in the jet. There are many different possible realizations of the scenario. For instance, the location of the photospheric radius in relation to the saturation radius will affect the strength of the blackbody and different magnetizations of the outflow will change the ratio between the two components [19].

As mentioned above, identifying a blackbody component in the spectrum can alleviate some of the difficulties facing interpretations suggesting a synchrotron origin for the Band component. Many observed GRBs have hard spectra below their \( \nu F_\nu \) peaks. Those with indices \( \alpha > -1.5 \) below this peak cannot possess electrons that radiate synchrotron emission in the expected fast cooling regime, within this spectral window; this is the so-called fast-cooling \( \alpha \) index limit [20]. Models including a low-energy blackbody component allow for softer slopes of the Band component, thereby making the interpretation more compatible with synchrotron.

Spectra with hard \( \alpha \) slopes are however not the only issue facing synchrotron interpretations. Studying the widths of spectra, it can be seen that most are too narrow to accommodate synchrotron emission from realistic electron distributions [21]. This is shown in Fig. 4. In these cases adding a blackbody component will not help, but rather worsen the issue; the width of the Band function component in a composite spectrum is if anything more narrow than the entire spectrum.

An alternative to multiple emission zones is that the entire spectrum arises from the photosphere. This of course requires a radical departure from the framework where photospheric emission is described by a (single or multicolor) blackbody. One suggested way of altering the spectrum is subphotospheric emission. Different models propose different origins, such as magnetic reconnection [22], internal shocks [23] or collisional dissipation [24]. By varying the amount of dis-
Most GRB spectra do not look thermal, and many instead having multiple components. This can be interpreted as radiation from two separate emission regions, or as pure photospheric emission. Understanding the role of the photosphere is thus important to probe the physics of the outflow itself. Polarimetry provides a possible way to determine the contribution of the photosphere. There are today several proposed missions capable of measuring polarization in GRBs, which promises new insight into the physics of the relativistic jet.

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