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Can the Thermal Evolution of an Expanding Fireball Explain the GRB 221206B?

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The prompt phase emission mechanism of Gamma-Ray Bursts (GRB) is still an open question. The GRB spectrum is often well-fitted by an empirical smooth broken power-law function termed as the Band model. However, with the detection of a large population of GRBs, it was realised the presence of a thermal component along with the non-thermal counterpart is evident in the prompt spectra. To understand the prompt emission from GRB, we perform a detailed study of the relativistically expanding fireball model with its temperature evolving as a function of its radius. The numerical code developed under this scenario is coupled with XSpec as a local model and used to fit the time-averaged spectrum of a recently detected GRB 221206B by *Fermi*-GBM. We find the spectra can be fitted with an expanding fireball model in combination with a power law. Our fit results suggest the emission is dominated by the thermal process with photospheric radius r_{ph} of $13.64^{0.08}_{-0.07}$ log cm and photospheric temperature T_{ph} of $658.5^{-50.4}_{35.5}$ keV.

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1. Introduction

The early prompt phase of the Gamma-ray bursts (GRB) is highly variable and short-lived in γ-ray, and hard X-ray. Though rigorous studies have been carried out for more than five decades on the prompt phase of the GRBs, the radiation mechanism is still under debate([1], [2]). During the BATSE era, most GRBs showed a non-thermal spectrum that fitted well with the Band function([3]). The standard internal shock model is a common explanation for the non-thermal component in the spectrum, as an outcome of the synchrotron radiation or synchrotron self-Compton scattering from relativistic electrons ([4]). However, after the advent of *Fermi*, our understanding of the prompt phase of GRBs is revolutionised. In the recent detections, there were samples of GRBs with a much narrower energy spectrum, which supports the thermal origin of the prompt phase. Nevertheless, only a small population has been explained by a simple Planck function and the majority of GRBs are unable to be expressed by either a thermal or non-thermal component alone.

It was found that for a large sample, the emission from the photosphere surface of a relativistic expanding fireball can explain the GRB spectra. The radiation becomes transparent to the fireball beyond the photospheric radius where the optical depth (in the observer's frame) reduces less than unity. Further, the light travel time effect yields a broadened black body spectrum, which is the superposition of multiple Planck functions(mBB) at different temperatures. In this work, we developed an mBB model that is mainly governed by four parameters, the innermost radius from which information can reach the observer or the photospheric radius at on-axis angle r_{ph}, the photospheric temperature T_{pho}, the bulk Lorentz factor Γ of the expanding plasma and temperature variation index α.

The mBB model was applied to the recently detected burst GRB 221206B detected by the Fermi Gamma-ray Burst Monitor (GBM). Even though the spectrum of GRB 221206B can be well explained by the Band function, its low-energy spectral index exceeded the synchrotron limit. We show the GRB 221206B spectrum can be explained by a hybrid model of a multi-temperature blackbody(mBB) model in addition to a power law. The burst spectrum was found to be thermal-dominated similar to the bursts reported earlier such as GRB 021221([5]) and GRB 220426A ([6]).

2. Multi-Temperature Black Body Spectrum

In the standard fireball model for the GRBs, the thermalised radiation produced in outflow escape near the photospheric radius (r_{ph}), the last scattering surface of photons originally trapped in the ejecta. For the relativistically expanding spherical symmetric wind, the photospheric radius is found to have angle dependence ([7], [8]) $r_{ph} = r_{ph}(\theta)$. Thus, it can be inferred that the observed spectrum is a superposition of a series of different temperature black bodies integrated over an opening angle of θ.

A schematic of the spherically symmetric relativistically expanding wind with the velocity β is represented in Figure 1. The *equal time surface* observed at a distance D_L from the source by an observer is represented by the curve line in the figure 1. The evolution of the *equal time surface* is expressed as $(1 - \beta\cos(\theta))/(1 - \beta)$, which is the ratio of the on-axis radius r, to the radius at an angle θ, r_θ ([9]). The radiation reaching the observer from the *equal time surface* will have a

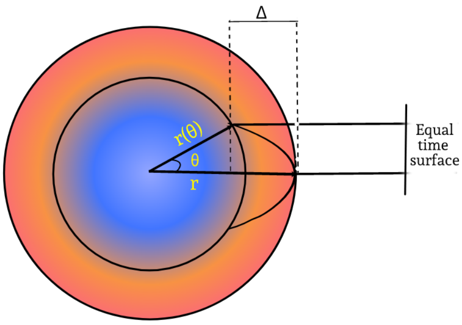

Figure 1: The schematic representation of an expanding fireball.

temperature gradient. The radiation from θ having temperature T_θ will be hotter than the on-axis radiation with temperature T_r at a giver radius r and is represented as

$$T_\theta = T_r \left[\frac{r}{r_\theta}\right]^\alpha \tag{1}$$

where, α is the temperature variation index, ranging from 0.0 to $2/3$ depending on the energetic of the fireball. The on-axis temperature (T_r) can be expressed in terms of on-axis photospheric temperature T_{ph0} as $T_{ph0} \times (r_{ph0}/r)^\alpha$, where r_{ph0} is the photospheric radius at $\theta = 0$. Further, the opening angle of the emission cone θ which can have a maximum value of $1/\Gamma$, becomes significantly smaller during the initial evolutionary phase of the fireball. The θ is governed by the condition $r_\theta \geq r_{ph}(\theta)$, that is

$$\frac{r_d}{\pi r(1-\beta)}\left(\frac{\theta}{\sin\theta} - \beta\right)(1-\beta\cos\theta) \leq 1 \tag{2}$$

where r_d is the observed radius of the opaque disk for photons from infinity([7]). Hence the opening angle ϕ is a minimum of either$1/\Gamma$ or θ. Following this we obtain the observed instantaneous flux from the expanding fireball as

$$F_\nu = \frac{4\pi h(1-\beta)^2}{c^2 D_L^2} r^2 \nu^3 \int\limits_{cos\phi}^{1} \frac{\mu}{(1-\beta\mu)^2} \frac{1}{\left\{\exp \frac{h\nu}{kT_{ph0}} \left[\left(\frac{1-\beta}{1-\beta\mu}\right)\left(\frac{r}{r_{ph0}}\right)\right]^\alpha - 1\right\}} d\mu \tag{3}$$

2.1 Radially Averaged Spectrum

The relativistically expanding fireball evolves from the radius r_1 to r_2 during the burst duration of t, where $r_2 = 2\beta c\Gamma^2 t + r_1$. Hence the final radially-averaged spectrum from the expanding fireball over the time t measured by an observer, termed as multi-temperature black body (mBB) will be

$$\mathscr{F} = \frac{\int\limits_{r_1}^{r_2} F_\nu(r)dr}{r_2 - r_1} \tag{4}$$

The temperature variation added to the effect of the spectrum integrated over the burst duration results in the GRB spectrum being wider compared to the Black-Body spectrum (the middle panel of Figure 2).

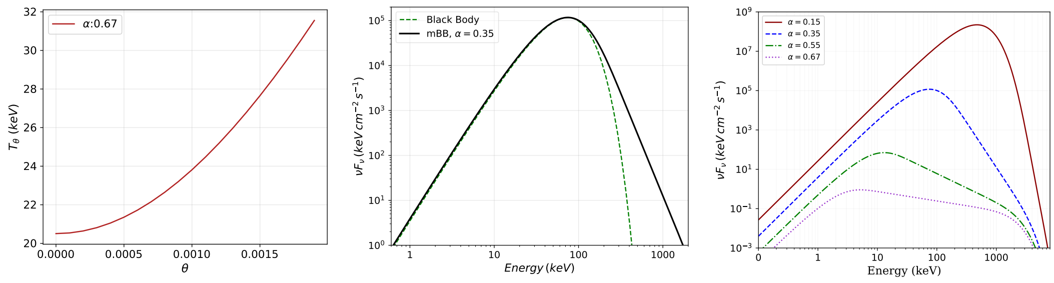

Figure 2: The left plot depicts the variation of temperature with the viewing angle for the variation index, α as $2/3$. The middle plot shows a significant deviation of the mBB model spectrum from the black body spectrum for α=0.35. The mBB spectrum for different temperature variation indices is illustrated in the right plot.

3. Observation and Data Reduction

GRB 221206B triggered by GBM (Fermi team 2022) onboard *Fermi* at 2:22:47 UT on 6 Dec 2022. The best-on-ground *Fermi* GBM position is 251.1, 44.5 (RA, Dec) degrees(J200) with uncertainty in the radius of 1 deg. The GBM light curve comprises two bright emission peaks with the T_{90} duration of a total of 9.6 s (in a 50-300 keV energy channel). The event fluence (10-1000 keV) in this time interval is (2.19 ± 0.05)E-06 erg/cm^2. ([10]). The significant brightness of this GRB warrants a detailed spectral analysis.

We obtained the time-tagged event (TTE) mode Fermi GBM data from the Fermi GBM trigger catalogue [1] using gtburst software[2]. We studied the temporal and spectral prompt emission properties of GRB 221206B using the brightest sodium iodide detectors NaI 2 with source observing angles of 36 degrees. We used RMFIT version 4.3.2 software7 to create the energy-resolved prompt emission light curve using Fermi GBM observations. We recalculated the T_{90} of the GRB n2 detector in the energy range 50-300 keV using the Bayesian block technique ([11]).

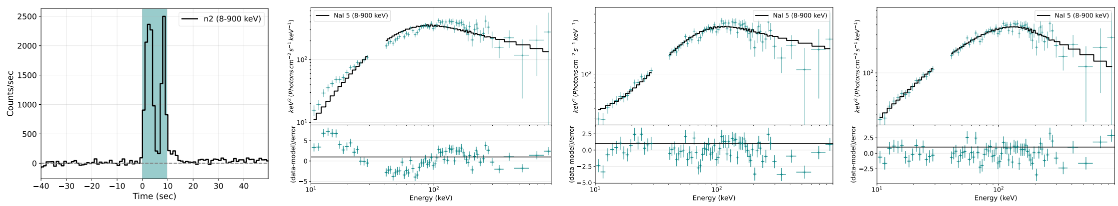

Figure 3: The spectral fit results for the shaded region (teal) of the light curve fitted with the mBB (second plot), mBB+power law (third plot) and the Band function (rightmost plot).

3.1 Spectral Analysis

For the spectral analysis, we used the same NaI detector as used for the temporal analysis. We obtained the time-averaged Fermi GBM spectra (from T0 to T0 + 9.6 s) using Make spectra for the XSPEC tool of gtburst software from Fermi Science Tools. The background (around the burst main

[1] https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigtrig.html
[2] https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/gtburst.html

emission) is fitted by selecting two temporal intervals, one interval before the GRB emission and another after the GRB emission. We performed the modelling of the GBM time-averaged spectra using the XSPEC software to investigate the possible emission mechanisms of GRB 221206B. The pgstat statistics information criteria are used for optimization, testing, and finding the best-fit model of the various models used. We consider the GBM spectrum over the energy range of 8- 900 keV for the spectral analysis. However, we ignore the 33–40 keV energy range due to the presence of the iodine K-edge at 33.17 keV while analyzing the NaI data.

We modelled the time-averaged GBM spectrum with the Band or GRB function ([3]). The fitted parameters obtained were low energy spectral index, α_{band} as $-0.3701^{-0.09}_{0.09}$, high energy spectral index, β as $-2.68^{-0.47}_{0.22}$ and peak energy, E_{peak} as $80.66^{-8.64}_{10.52}$ keV. The α_{band} above synchrotron limit suggested the presence of the thermal component in the spectra. The multi-temperature black body model (mBB, refer section 2) was then fitted for the hard limit of temperature variation index, α of 0.67([12]) and a typical value of the bulk Lorentz factor of 300. We obtained the best-fit model parameter on-axis photospheric radius (r_{ph}) and photospheric temperature (T_{ph}) of $13.64^{-0.07}_{0.08}$ log cm and $685.5^{-50.4}_{35.5}$ keV respectively. Since the mBB model alone could not explain the GRB 221206B spectrum, a power law component was added to address the non-thermal contribution in the burst spectrum. We found that the mBB along with the power law component is the best-fit model, where the photon index is $1.83^{-0.05}_{0.04}$. Our analysis concludes that the GRB 221206B spectrum is thermally dominated and best described by a hybrid model (mBB+power law).

4. Summary and Discussion

The presence of the thermal component along with the non-thermal component in the GRB spectrum is supported by various observations ([5], [6], [13]). These results have motivated us to examine the emission process under a realistic fireball scenario. We construct a multi-temperature black body spectrum resulting from expanding fireball and the numerical code developed under this model is coupled with XSpec for detailed studies of GRBs.

The simple Band spectral fit of GRB 221206B hinted at the presence of a strong thermal component. We found that this GRB was well-fitted by a mBB model accompanied by a power law. The burst was thermally dominated, with the flux ratio of the thermal to the non-thermal component as 3.50. Our fit results suggest the photospheric radius (r_{ph}) from where the radiation originates was found to be $13.64^{-0.07}_{0.08}$ log cm and the temperature at this radius was $685.5^{-50.4}_{35.5}$ keV.

A significant sample of GRB is explained by hybrid models with varying thermal to non-thermal dominance. This leads to diverse explanations for the emission process as well as the nature of the fireball (radiation-dominated or matter-dominated); which directs us to open questions regarding the emission process of the prompt phase of GRBs. In the future, more sensitive and broad-band observations of the GRB prompt emission spectrum will help better understand the prompt phase of the GRBs.

5. Acknowledgement

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