E_P and α Dual-Tracking of the Energy Spectrum Characteristics of GRB131231A (Postprint)

Authors: Wang Chen, Peng Chaoyang, Chen Jiaming

Date: 2022-04-14T00:00:00+00:00

Abstract

GRB 131231A is a special burst exhibiting 'dual-tracking' behavior in EP and α. To further analyze the spectral characteristics of this burst, we performed detailed time-resolved spectroscopy using a Bayesian method and found that 16 out of 24 resolved spectra show clear thermal components. These thermal components are mainly distributed in the early phase of the pulse and near its peak, supporting the transition of the GRB jet from matter-dominated to magnetically-dominated. After adding the thermal component, the parameters EP and α both hardened, while the peak flux Fp remained almost unchanged. Using the photospheric component, we calculated the characteristic parameters of the relativistic outflow and found that the outflow characteristic parameters —the initial radius r0, saturation radius rs, photospheric radius rph, and the Lorentz factor during the coasting phase—all underwent relatively obvious evolution. The temperature evolution over time can also be fitted with a broken power-law model, with power-law indices of a = 7.65\$$\pm 3.48 and b = -2.10 \pm$\$3.48 for the rising and decaying phases, respectively. The decaying index b shows a large deviation from the value of approximately -2/3 obtained in previous studies.

Full Text

Study on the Energy Spectrum Characteristics of the "Double-Tracking" E_p and α in GRB 131231A

Wang Chen, Peng Zhao-Yang[+], Chen Jia-Ming
College of Physics and Electronic Information, Yunnan Normal University, Kunming 650500, China
Email: pengzhaoyang412@163.com

Abstract

GRB 131231A is a special gamma-ray burst exhibiting "double-tracking" behavior in both E_p and α. To further analyze its spectral characteristics, we performed detailed time-resolved spectroscopy using Bayesian methods. Our analysis of 24 resolved spectra revealed that 16 contain significant thermal components, predominantly distributed during the early and peak phases of the pulse. This supports the scenario of a GRB jet transitioning from matter-dominated to magnet-dominated outflow. After incorporating thermal components, the parameters E_p and α both hardened, while the peak flux F_p remained essentially unchanged. By calculating the properties of the relativistic outflow from the photospheric component, we found that the outflow characteristic parameters —including the initial radius r_0, saturation radius r_s, photospheric radius r_{ph}, and the coasting Lorentz factor Γ—all evolved significantly. The temperature evolution over time can be fitted with a broken power-law model, with power-law indices of $a = 7.65 \pm 3.48$ for the rising phase and $b = -2.10 \pm 3.48$ for the decaying phase. However, the decay index b shows substantial deviation from the value close to $-2/3$ obtained in previous studies of other thermal pulses.

Keywords: Fermi gamma-ray burst; prompt emission spectrum; spectral fitting; data analysis; optimal model

1. Introduction

Research on gamma-ray bursts (GRBs) has spanned over fifty years, yet fundamental questions about their prompt emission remain puzzling. Among the most basic questions is the composition of the jet—whether it is a baryon-dominated fireball or a Poynting-flux-dominated outflow—which determines or at least strongly influences the energy dissipation mechanism (shocks or magnetic reconnection), particle acceleration mechanism (thermal or magnetically dominated), and particularly the radiation mechanism (synchrotron radiation or Comptonization of photospheric quasi-thermal radiation) [**?**]. GRB radiation comprises two main phases: prompt emission and afterglow. The prompt phase typically lasts from seconds to minutes and exhibits rich observational features, most of which remain poorly explained. The spectral components during this phase originate from two primary sources: synchrotron emission (non-thermal component) and the photosphere (thermal component) [**?**].

Previous studies have identified three fundamental components in GRB spectra [**?**]: (1) a non-thermal component that can be fitted by the Band function; (2) a thermal component that can be fitted by a Planck function; and (3) a power-law component appearing at higher energies. Observed GRBs typically exhibit two or more of these components [**?**]. Thermally dominated GRBs are extremely rare, so composite models are commonly employed in spectral analysis, with the Band or cutoff power-law (CPL) models serving as the base models. In most cases, composite models yield better parameter values, which helps us infer the

GRB energy mechanism and central engine.

During the BATSE era, E_p displayed several distinct evolutionary patterns: (1) a "hard-to-soft" trend, monotonically decreasing regardless of flux variations [?, ?]; (2) a "flux-tracking" trend, where the parameter evolution follows the flux rise and fall [?]; and (3) a "soft-to-hard" trend or chaotic evolution [?]. After the launch of the Fermi satellite in 2008, extensive observational data confirmed that the first two patterns dominate: approximately two-thirds show "hard-to-soft" evolution, while about one-third exhibit "flux-tracking" [?]. The physical origins of these evolutionary patterns remain unresolved, although several scenarios have been proposed in the literature [?, ?]. Compared to E_p evolution, α evolution appears more chaotic and has consequently received less attention and physical interpretation.

Li Liang discovered that both E_p and α evolution in GRB 131231A exhibit flux-tracking behavior, defining this as the spectral evolution "double-tracking" mode [?]. However, Li et al. did not incorporate thermal components in their detailed spectral analysis. Since numerous studies have demonstrated that GRB spectra contain thermal components, we have applied Bayesian blocks and Markov Chain Monte Carlo (MCMC) methods to GRB 131231A to investigate the spectral characteristics of this double-tracking behavior more thoroughly. In GRB research, subdominant thermal components typically appear on the low-energy side of the Band spectrum [?, ?]. Addressing this phenomenon, Li Liang investigated the impact of thermal components on non-thermal spectral parameters in eight GRBs with prominent thermal emission, using CPL as the base model combined with a blackbody (BB) component [?]. For the vast majority of GRB time-resolved spectra, the CPL model is adequate [?, ?], though in some cases the high-energy power-law index β of the Band model significantly improves the fit. In the synchrotron scenario, β provides information about particle acceleration and shock properties, while in the photospheric scenario it offers insights into energy dissipation in the radiation region [?]. Given these considerations, we adopt the Bayesian Information Criterion (BIC) as our selection standard [?], choosing the optimal model for each time interval in the GRB and investigating how spectral parameters change after applying this optimal model selection to GRB 131231A.

2. Data Processing and Analysis Methods

GRB 131231A (trigger number: 131231198) was detected by the Gamma-ray Burst Monitor (GBM: 8 keV–40 MeV) aboard the Fermi satellite on December 31, 2013. In this work, we employ the Bayesian analysis package known as the Maximum Likelihood framework (3ML) for all spectral analyses. This toolkit utilizes Markov Chain Monte Carlo (MCMC) theory to process time-resolved spectra; the advantages of this method are described in [?]. We obtained Fermi GBM data [?] from the website (https://fermi.gsfc.nasa.gov/). Among the three available data types–CTIME, CSPEC, and TTE files–we selected TTE files with the finest time resolution (2 s) for our analysis.

In these MCMC fitting examples based on Bayesian statistics, we use the Bayesian Information Criterion (BIC) [?] to determine the optimal spectral model, comparing the difference in BIC values (ΔBIC) between different models to identify the best one. Generally, the Band model [?] and the CPL model [?] are two superior options for GRB fitting. We selected these as our base models and combined each with the BB model. For each time-resolved spectral interval of the GRB, we performed model comparisons to select the most appropriate optimal model.

To better study spectral evolution over time, performing time-resolved spectral binning is an effective approach. Burgess examined four tools for slicing light curves into temporal bins [?], among which signal-to-noise ratio (S/N) and Bayesian blocks (BBs) [?] are the most effective. He noted that each method has advantages and disadvantages: traditional S/N binning ensures sufficient photons in each time interval for spectral fitting but can sometimes destroy physical structures. The pros and cons of Bayesian blocks are discussed in [?]. We adopted Bayesian block partitioning but still used S/N as a filtering method to eliminate intervals that did not meet certain criteria (in this work, we selected intervals with S/N $\geq$ 20, as intervals with S/N $<$ 20 produce large errors during fitting [?]). The combined use of these two methods yields more meaningful intervals.

Table 1 provides the relevant parameters for this burst. Note: CPL1 represents time-resolved spectral intervals with ΔBIC $\leq$ -8 using the CPL model, while CPL2 represents intervals with -8 $<$ ΔBIC $<$ 8 using the CPL model. Figure 1 [Figure 1: see original paper] presents an example of a resolved spectral fit result.

We fitted GRB131231A using the Band function model, Compton function model, and Planck function model, obtaining their time-resolved spectral data as shown in Table 2 . Based on the ΔBIC values from the time-resolved spectra, some bursts show better CPL model fits in certain time intervals, while others show better Band model fits. After comprehensive consideration, we performed optimal model selection for each time-resolved spectral interval of each burst. Our selection method uses the BIC difference produced when fitting each interval separately with the CPL model versus the Band model as the screening criterion: when ΔBIC $\leq$ -8, we consider the interval more suitable for the CPL model; when ΔBIC $>$ 8, the Band model is preferred; when -8 $<$ ΔBIC $<$ 8, we consider the CPL model more appropriate (when neither model shows clear superiority, the model with fewer parameters is generally selected). We then determine whether the interval contains a thermal component by checking if the BIC difference between the selected base model and the base model plus BB component is greater than or equal to 8. Finally, we filter for intervals with S/N $\geq$ 20 as our research subjects, as shown in Table 4 .

During spectral analysis, the time span of individual intervals is much smaller than the overall time span. We assume that parameter variations within each time interval are quasi-static, using the parameter characteristics at the midpoint of the time interval to represent the behavior of the entire interval [?]. In this paper, we present the evolution diagrams of the GRB' s spectral parameters.

3. Analysis Results

3.1 Parameter Distributions Figure 2 [Figure 2: see original paper] displays the parameter distributions for the Best model, including α, E_p, and F_p. Table 2 lists the mean values and standard deviations of these distributions. We performed kernel density estimation (KDE) for each parameter distribution using a Gaussian kernel. As shown in Table 2, the mean values of the low-energy photon index α distribution are -1.06 ± 0.29 without the blackbody component and -1.00 ± 0.29 with it. After adding the blackbody component, α becomes slightly harder, but both values are consistent with the typical value $\alpha \sim -1$ and remain above the so-called synchrotron "death line" ($-3/2 < \alpha < -2/3$). After adding the blackbody component, the peak of the E_p kernel density curve shifts to the right, with a mean value of 199.84 ± 161.61 keV. Compared to the case without the blackbody component, the peak energy E_p indeed hardens as well. Meanwhile, F_p shows no significant change before and after adding the blackbody component, with only a slight variation in the mean value. These results are consistent with previous studies.

3.2 Spectral Parameter Evolution Without Thermal Component We re-analyzed the evolution of peak energy and low-energy spectral index without incorporating the blackbody component. Figure 3 [Figure 3: see original paper] shows the data points corresponding to time-resolved spectral intervals with S/N $\geq$ 20 in the Bayesian blocks. The parameters E_p and α of GRB131231A exhibit a clear flux-tracking trend, consistent with the results obtained by Li Liang.

3.3 Spectral Parameter Evolution and Changes After Adding Thermal Component After incorporating the blackbody component, we identified 16 time-resolved spectral intervals with detected thermal components. The evolutionary trends of both E_p and α remain consistent with those without the thermal component, still displaying double-tracking behavior. As described in Section 3.1, these parameters changed: α and E_p hardened slightly. However, Figure 4 [Figure 4: see original paper] reveals the details of these changes. In GRB131231A, the overall variation of E_p values in intervals with thermal components is not uniform, as shown in Figure 4(a). We find that before the pulse peak, E_p hardens (increases) after adding the BB component; after the peak, E_p softens (decreases). Specifically, six points show hardened E_p values, all distributed before the peak, while ten points show softened E_p values, all distributed after the peak.

The overall change in α for GRB131231A is also non-uniform, as shown in Figure 4(b). One point lies above the synchrotron death line, while the rest are distributed below it. After adding the BB component, α shows noticeable changes: before the peak, α softens; after the peak, it hardens. Before adding the blackbody component, only the last two points in GRB131231A had α values less than $-3/2$; after adding the thermal component, two points at the pulse peak rise above the synchrotron death line, while the last two points increase slightly but remain below $-3/2$.

3.4 Spectral Parameter Correlations Correlation analysis plays an important role in understanding GRB physics, as it provides clues to reveal their nature. We examined $\log(E_p)$-$\log(F_p)$, $\log(F_p)$-α, and $\log(E_p)$-α relationships. Table 3 provides the specific correlation coefficients. The strength of correlation is given by Spearman' s coefficient r, with strong correlation defined as $r > 0.7$ and weak correlation as $r < 0.4$. References [**?**, **?**, **?**] reveal that the $\log(F)$-α relationship mainly has three types: non-monotonic (containing both positive and negative power-law segments, typically with a clear break at peak flux), monotonic (described by a single power law), and no clear trend.

For GRB131231A, the $\log(F_p)$-$\log(E_p)$ correlation in the three models shows: Best: $r = 0.426$, $p = 0.0378$; Band: $r = 0.687$, $p < 10^{-4}$; CPL: $r = 0.566$, $p < 10^{-4}$, with the Band model performing best. The $\log(E_p)$-α correlation shows: Best: $r = 0.412$, $p = 0.0453$; Band: $r = 0.70$, $p = 0.00014$; CPL: $r = 0.731$, $p < 10^{-4}$, again with the Band model performing best. The $\log(F)$-α correlation shows: Best: $r = 0.765$, $p < 10^{-4}$; Band: $r = 0.655$, $p = 0.00052$; CPL: $r = 0.756$, $p < 10^{-4}$, with the Best model performing best. In the Band and CPL models, $\log(E_p)$-$\log(F)$, $\log(F_p)$-α, and $\log(E_p)$-α all show extremely strong correlations. When using the Best model, the correlations of $\log(F_p)$-$\log(E_p)$ and $\log(E_p)$-α both worsen, while the $\log(F_p)$-α correlation becomes stronger than in the Band and CPL models.

3.5 Thermal Component Analysis To examine thermal components in the spectra, we first identified the optimal model for each time-resolved spectrum, then fitted it with the optimal model plus a BB component, and examined the difference in BIC statistics (ΔBIC) before and after adding the blackbody. If ΔBIC < -8, the spectrum significantly contains a thermal component. Figure 5(a) [Figure 5: see original paper] shows the evolution and distribution of ΔBIC across the pulse, while Figure 5(b) shows the ratio of thermal component flux to total energy flux.

GRB131231A has distinct pulse rise and decay phases. We statistically analyzed the regions where thermal components appear. The statistical results from Figure 5(a) indicate that spectra with ΔBIC < -8 mainly correspond to positions on the light curve with high photon counts, suggesting that thermal components primarily exist in the early pulse stage and gradually decrease over time. Figure 5(b) shows that the ratio of thermal component flux to total energy flux is mostly distributed below 0.1, with higher ratios mainly found in high pulse regions.

3.6 Parameters Related to Thermal Component Current research suggests that thermal components originate from the photosphere. According to the high-latitude radiation interpretation, the highest temperature and strongest thermal flux are initially emitted from the photosphere along the jet axis toward the observer. Therefore, in principle, the radius of the photon emission location can be determined [?]. Following the theory in [?], for a GRB with known redshift, when we know the observed temperature and thermal energy flux, we can calculate the initial radius r_0 of the outflow (the distance from the central engine to the jet ejection point). For cases where $r_{ph} > r_s$, we can further calculate the saturation radius r_s, photospheric radius r_{ph}, and the coasting Lorentz factor Γ of the outflow.

Using Equation (1) from [?], we can determine the relative positions of the photosphere and saturation layer. We find that all intervals with thermal components in GRB131231A satisfy $(F_{BB}/F_{NT})^{3/2} > 1$, so we conclude that the photospheres of all shells in this burst lie above the saturation layer ($r_{ph} > r_s$). Therefore, we apply the theory from [?] to calculate the initial radius r_0, saturation radius r_s, photospheric radius r_{ph}, and coasting Lorentz factor Γ for this burst.

We can obtain the parameter R related to the thermal component, which can be interpreted as the effective transverse scale of the radiation zone [?]. A constant R implies that the effective radiation region of the photosphere is time-independent. We can calculate the R value for the GRB through the following relation:

$$\sigma_{SB}T^4 = \frac{F_{BB}}{(1+z)^2}\frac{4\pi d_L^2\Gamma^4}{R^2}$$

where σ_{SB} is the Stefan-Boltzmann constant (in units of erg s^{-1} cm^{-2} K^{-4}), F_{BB} is the observed blackbody energy flux (in units of erg s^{-1} cm^{-2}), T is the observed blackbody temperature (in keV), z is the cosmological redshift of the GRB, d_L is the luminosity distance (in cm), and Γ is the Lorentz factor during the coasting phase.

As shown in Figure 6(a) [Figure 6: see original paper], R exhibits rapid increase during the pulse onset stage, showing no monotonic increasing trend after 22 s, with relatively gentle variations. The angle between the outflow velocity direction and the line of sight is θ. After the pulse peak, radiation from the $\theta = 0$ region weakens and high-latitude radiation becomes dominant [?], at which point the effective radiation region of the photosphere becomes time-independent.

To analyze the temperature evolution over time, Ryde derived a broken power-law model for temperature based on the model in [?] [?]. The broken power-law form is given by Equation (6) in [?]. We used it to fit the temperature versus time for intervals with detected thermal components in this burst, as shown in Figure 6(b). The fitted parameters corresponding to Equation (6) are $\Phi = 2.77 \pm 2.44$,

$t_0 = 24.59 \pm 0.95$, $\xi = -4.88 \pm 2.49$, and $\delta = 0.0028 \pm 1.08$. From these fitted parameters, we obtain power-law indices of $a = 7.65 \pm 3.48$ for the rising phase and $b = -2.10 \pm 3.48$ for the decaying phase.

The Lorentz factor of GRB131231A shows an evolution of first increasing then decaying over time, with an initial value of 157 ± 0.5 and a peak value of 385.6 ± 0.34. It can be well fitted by a broken power law, as shown in Figure 7(a) [Figure 7: see original paper], with a rising power-law index of $\alpha_1 = 1.37 \pm 0.39$ and a decaying index of $\beta_1 = -1.38 \pm 0.39$. S. Iyyani found that in GRBs with significant photospheric components, the Lorentz factor decreases monotonically with time as $\Gamma \propto (F/R)^{1/4} Y^{1/4}$ [?, ?]. During the pulse rising phase, the increase rates of total flux F and R are nearly identical, making the Lorentz factor nearly constant or only weakly decaying. Our obtained Lorentz factor shows an initial increase followed by decay, which does not conform to the traditional photospheric model prediction of an approximately constant Lorentz factor during the initial stage.

The initial radius marks where the jet begins to accelerate. In GRB131231A, r_0 starts from an initial value of $(3.6 \times 10^6 \pm 1.56 \times 10^6) Y^{3/2}$ cm, rises with the light curve, and reaches a maximum of $(1.39 \times 10^8 \pm 5.17 \times 10^7) Y^{3/2}$ cm at the pulse peak (22 s), though it does not track the light curve well. After the pulse peak, r_0 shows another rising trend, possibly due to reactivation of the central engine, and then declines to $(6.9 \times 10^5 \pm 1.02 \times 10^6) Y^{3/2}$ cm in the late pulse stage, below the initial value. The variation magnitude of r_0 spans 10^6-10^8 cm, a range between the black hole horizon radius (10^{6-7} cm for a black hole mass of 5-10 $M_\odot$) and the core size of a Wolf-Rayet progenitor star, suggesting that r_0 is related to the interaction between the jet and the progenitor star [?, ?].

The saturation radius r_s evolves similarly to the initial radius during the pulse, differing by nearly three orders of magnitude in value. The initial value of r_s is $(5.7 \times 10^8 \pm 2.46 \times 10^8) Y^{5/4}$ cm, with a maximum of $(4.72 \times 10^{10} \pm 1.76 \times 10^{10}) Y^{5/4}$ cm and a minimum of $(1.2 \times 10^8 \pm 1.83 \times 10^8) Y^{5/4}$ cm during evolution.

The photosphere is the deepest region from which photons can escape. From pulse onset to peak (22 s), the photospheric radius r_{ph} tracks the pulse rise, increasing from an initial value of $(2.06 \times 10^{11} \pm 8.68 \times 10^{10}) Y^{1/4}$ cm to a maximum of $(1.1 \times 10^{12} \pm 5.89 \times 10^{10}) Y^{1/4}$ cm near the pulse peak. After the pulse peak, r_{ph} declines rapidly, varying within one order of magnitude, followed by only weak changes. The minimum photospheric radius in GRB131231A is $(1.41 \times 10^{11} \pm 6.87 \times 10^{11}) Y^{1/4}$ cm. The r_{ph} evolution during the pulse decay phase is consistent with that observed in GRB110721A [?], GRB140329B, and GRB160625B [?]. The relation $r_{ph} \propto \Gamma^2$ holds, where L_0 is the total kinetic luminosity of the GRB and M is the baryon load, satisfying $M = L_0/\Gamma c^2$. During the pulse rising phase, as r_{ph} increases with the pulse, Γ also increases with time, requiring L_0 or M to increase at an even faster rate. The increase in baryon load leads to more associated electrons, increasing opacity and thus the photospheric radius. During the pulse decay phase, both Γ and L_0 decrease, while r_{ph} remains constant or changes only weakly. For this situation to occur, $L_0 \propto \Gamma^3$ (or $M \propto \Gamma^2$) must be satisfied [?].

4. Conclusions and Discussion

GRB 131231A is a relatively bright, near-single-pulse long burst. We applied Bayesian methods using empirical and physical models—namely the CPL model, Band model, and Planck function model (BB)—to perform detailed time-resolved spectroscopy, conducting model comparisons for each interval to determine the optimal model. We obtained a total of 24 spectra and studied their properties. This GRB shows good flux-tracking behavior in both E_p and α values. The flux-tracking behavior of E_p may be related to two synchrotron models [?, ?]. Figure 2(b) shows that α values are distributed below the synchrotron death line, with the overall distribution being very consistent with the synchrotron model. Li et al. pointed out that during the rising phase, α becomes harder, indicating that electrons are evolving from the fast-cooling regime to the slow-cooling regime [?]. During the decaying phase, α observationally becomes softer, and the decay phase of broad pulses may be controlled by the "curvature effect" [?, ?, ?].

Through joint fitting with the optimal model and BB model, we detected 16 time-resolved spectral intervals with significant thermal components, indicating that this burst is not thermally dominated. Li Liang systematically studied the spectral properties of eight GRBs containing thermal components [?] and found that for non-thermally dominated GRBs, adding thermal components softens the α value, hardens E_c, and shows no significant difference in energy flux F_p across different models. For GRB 131231A, before the light curve peak, E_p hardens after adding the BB component, while after the peak it softens. Similarly, α softens before the peak and hardens after the peak. GRB131231A thus exhibits special spectral evolution.

The central engine of GRB jets is likely a hybrid system containing both a hot fireball component and a cold Poynting flux component [?]. Some bright bursts (e.g., GRB 090902B) show thermal-like time-resolved spectra at the beginning or near the peak of the pulse, with non-thermal time-resolved spectra appearing in subsequent pulses, possibly indicating a gradual change in jet composition [?]. Gao et al. provided a more comprehensive description of the origin of GRB jet composition through the hybrid jet model [?]. Li Liang analyzed eight Fermi GRBs using this method [?] and found that most bursts can be well explained by the hybrid jet scenario. Although the low-energy photon index α of GRB 131231A does not exceed the so-called synchrotron death line, the fitting statistics improve significantly after adding thermal components. Spectra with ΔBIC $<$ -8 are mainly concentrated in the pulse onset and peak phases (10–26 s), after which the thermal components gradually decrease, suggesting that the GRB may transition from a matter-dominated fireball to a magnetically dominated Poynting-flux outflow. The reappearance of thermal components in the late pulse stage may be caused by reactivation of the central engine.

Although the temperature can also be fitted with a broken power law, there are significant differences between the rising and decaying index values and those obtained by Ryde for thermal pulses in GRBs [?].

We calculated the parameters related to the thermal component: Γ, r_0, r_s, and r_{ph}. The Lorentz factor we obtained shows an initial increase followed by decay, which does not conform to the traditional photospheric model prediction of an approximately constant Lorentz factor during the initial stage [?, ?] followed by exponential decay. This may be caused by the internal shock model [?]. Another explanation is the birth of an isolated magnetar, where the Lorentz factor increases with time [?], but the luminosity of GRB131231A is much greater than that predicted by the magnetar model, making this scenario unlikely. The ranges of parameter values we obtained for r_0, r_s, and r_{ph} are consistent with those of GRBs with significant photospheric components such as GRB 081224A, GRB 090719A, and GRB 100707A [?, ?]. The evolution range of r_0 lies between the black hole horizon radius (10^{6-7} cm for a black hole mass of 5-10 $M_\odot$) and the core size of a Wolf-Rayet progenitor star, suggesting that r_0 is related to the interaction between the jet and the progenitor star [?]. The evolution behavior of r_s is similar to that of r_0, differing by within three orders of magnitude in value.

From pulse onset to peak (22 s), the photospheric radius r_{ph} tracks the pulse rise; after the pulse peak, r_{ph} declines rapidly, varying within one order of magnitude, followed by only weak changes. During the pulse rising phase, as r_{ph} increases with the pulse and Γ also increases with time, this requires L_0 or $\dot{M}$ to increase at an even faster rate. The increase in baryon load leads to more associated electrons, increasing opacity and thus the photospheric radius. During the pulse decay phase, both Γ and L_0 decrease, while r_{ph} remains constant or changes only weakly. This situation requires $L_0 \propto \Gamma^3$ (or $\dot{M} \propto \Gamma^2$) [?].

The special spectral evolution of GRB131231A warrants further in-depth study and theoretical explanation.

References

[1] Li L. Multipulse Fermi Gamma-Ray Bursts. I. Evidence of the Transition from Fireball to Poynting-flux-dominated Outflow[J]. The Astrophysical Journal Supplement Series, 2019.

[2] Li L. Thermal Components in Gamma-ray Bursts. I. How Do They Affect Non-Thermal Spectral Parameters?[J]. 2019.

[3] Zhang B B, Zhang B, Liang E W, et al. A Comprehensive Analysis of Fermi Gamma-Ray Burst Data. I. Spectral Components and Their Possible Physical Origins of LAT/GBM GRBs[J]. 2010.

[4] Guiriec S, Kouveliotou C, Daigne F, et al. TOWARD A BETTER UNDER-

STANDING OF THE GRB PHENOMENON: A NEW MODEL FOR GRB PROMPT EMISSION AND ITS EFFECTS ON THE NEW Luminosity-E_{peak}-L RELATION[J]. The Astrophysical Journal, 2015, 807(2):148-148.

[5] Norris J P, Share G H, Messina D C, et al. Spectral evolution of pulse structures in gamma-ray bursts[J]. Astrophysical Journal, 1986, 301(1).

[6] Bhat P N, Fishman G J, Meegan C A, et al. Spectral evolution of a subclass of Gamma-Ray Bursts observed by BATSE[J]. The Astrophysical Journal, 1994, 426(2).

[7] Hakkila J, Preece R D. Unification of Pulses in Long and Short Gamma-Ray Bursts: Evidence from Pulse Properties and their Correlations[J]. Physics, 2011, 740(2).

[8] Kargatis V E. Continuum spectral evolution of gamma-ray bursts[J]. Physics Astronomy & Astrophysics, 1996.

[9] Li L, Geng J J, Meng Y Z, et al. "Double-tracking" Characteristic of the Spectral Evolution of GRB 131231A: Synchrotron Origin?[J]. 2019.

[10] Oganesyan G, Nava L, Ghirlanda G, et al. Characterization of Gamma-Ray Burst prompt emission spectra down to soft X-rays[J]. 2017.

[11] Oganesyan G, Nava L, Ghirlanda G, et al. Prompt optical emission as a signature of synchrotron radiation in gamma-ray bursts[J]. Astronomy and Astrophysics, 2019.

[12] Band D L, Matteson J, Ford L, et al. BATSE observations of gamma-ray burst spectra. I - Spectral diversity[J]. The Astrophysical Journal, 1993, 413(1).

[13] Axelsson M, Baldini L, Barbiellini G, et al. GRB110721A: An Extreme Peak Energy and Signatures of the Photosphere[J]. The Astrophysical Journal Letters, 2012, 757(2):L31.

[14] Burgess J M, Greiner J, Bégué D, et al. A Bayesian Fermi-GBM short GRB spectral catalogue[J]. Monthly Notices of the Royal Astronomical Society, 2017, 490(1).

[15] Yu H F, Dereli-Bégué H, Ryde F. Bayesian Time-Resolved Spectroscopy of GRB Pulses.

[16] Li L, Ryde F, Pe' er A, et al. Bayesian Time-resolved Spectroscopy of Multipulse GRBs: Variations of Emission Properties among Pulses[J]. The Astrophysical Journal Supplement Series, 2021, 254(2):35 (48pp).

[17] Zhang B-B, Zhang B, Castro-Tirado A J, et al. Transition from fireball to Poynting-flux-dominated outflow in the three-episode GRB 160625B[J]. Nature Astronomy, 2018.

[18] Meegan C, Lichti G, Bhat P N, et al. The Fermi Gamma-Ray Burst Monitor[J]. The Astrophysical Journal, 2009, 702(1):791.

[19] Michael B J. On Spectral Evolution and Temporal Binning in Gamma-Ray Bursts[J]. Monthly Notices of the Royal Astronomical Society, 2014, 445(3):2589-2598.

[20] Scargle J D, Norris J P, Jackson B, et al. Studies in Astronomical Time Series Analysis. VI. Bayesian Block Representations[J]. The Astrophysical Journal, 2012, 764(2).

[21] Gruber D, Goldstein A, Ahlefeld V V, et al. The Fermi GBM Gamma-Ray Burst Spectral Catalog: Four Years Of Data[J]. The Astrophysical Journal Supplement Series, 2014, 211(1).

[22] Iyyani S, Ryde F, et al. Variable jet properties in GRB110721A: time resolved observations of the jet photosphere[J]. MNRAS, 2013, Vol.:2739-2748.

[23] Preece R D, Briggs M S, Mallozzi R S, et al. The BATSE Gamma-Ray Burst Spectral Catalog. I. High Time Resolution Spectroscopy of Bright Bursts using High Energy Resolution Data[J]. The Astrophysical Journal Supplement Series, 2008, 126(1):19-36.

[24] Firmani C, Cabrera J I, Avila-Reese V, et al. Time-resolved spectral correlations of long-duration γ-ray bursts[J]. Monthly Notices of the Royal Astronomical Society, 2009.

[25] Ghirlanda G, Nava L, Ghisellini G. Spectral-luminosity relation within individual Fermi gamma rays bursts[J]. Astronomy & Astrophysics, 2010, 511(2):A43.

[26] Pe' er A, Ryde F, Wijers R A M J, et al. A NEW METHOD OF DETERMINING THE INITIAL SIZE AND LORENTZ FACTOR OF GAMMA-RAY BURST FIREBALLS USING A THERMAL EMISSION COMPONENT[J]. The Astrophysical journal, 2007, 664(1Pt2):L1-L4.

[27] Ryde F, Pe' er A. Quasi-blackbody component and radiative efficiency of the prompt emission of gamma-ray bursts[J]. 2008.

[28] Ryde F. Smoothly Broken Power Law Spectra of Gamma-Ray Bursts[J]. Astrophysical letters & communications, 1998, 39(1).

[29] Iyyani S, Ryde F, et al. Synchrotron emission in GRBs observed by Fermi: its limitations and the role of the photosphere[J]. Monthly Notices of the Royal Astronomical Society, 2016.

[30] Uhm Z L, Zhang B. TOWARD AN UNDERSTANDING OF GRB PROMPT EMISSION MECHANISM: II. PATTERNS OF PEAK ENERGY EVOLUTION AND THEIR CONNECTION TO SPECTRAL LAGS[J]. The Astrophysical journal, 2020.

[31] Kumar P, Panaitescu A. Afterglow Emission from Naked Gamma-Ray Bursts[J]. The Astrophysical Journal, 2000, 541(2):L51-L54.

[32] Uhm Z L, Zhang B. ON THE CURVATURE EFFECT OF A RELATIVISTIC SPHERICAL SHELL[J]. Astrophysical Journal, 2015, 808(1):33.

[33] Uhm Z L, Zhang B. TOWARD AN UNDERSTANDING OF GRB PROMPT EMISSION MECHANISM. I. THE ORIGIN OF SPECTRAL LAGS[J]. Astrophysical Journal, 2016, 825(2).

[34] Gao H, Zhang B. Photosphere emission from a hybrid relativistic outflow with arbitrary dimensionless entropy and magnetization in GRBs[J]. Astrophysical Journal, 2014, 801(2).

[35] Axelsson M, Zhang B B, et al. Identification and properties of the photospheric emission in GRB090902B[J]. The Astrophysical Journal Letters, 2010, 709(2):L172.

[36] Hascoët T R, Daigne F, Mochkovitch R. Prompt thermal emission in gamma-ray bursts[J]. Astronomy & Astrophysics, 2013, 551(3): págs. 1075-1082.

[37] Metzger B D. Gamma-Ray Burst Central Engines: Black Hole Versus Magnetar[J]. arXiv, 2010.

Table 4: Best Model Fitting Results for the Time-Resolved Spectrum of GRB 131231A

T_{start}:T_{end}	Model	S/N	α	E_p (keV)	kT (keV)	F_p (erg $s^{-1}cm^{-2}$)	F_{BB} (erg $s^{-1}cm^{-2}$)	BIC
12.0:14.17	CPL2+BB	:0.09	$-0.95\pm$ 0.09	:24.9	162.28± 27.1	:3.75E-08	$7.46\times10^{-7}\pm3.35\times10^{-8}$	:0.11
14.17:15.32	CPL2+BB	:0.09	$-1.02\pm$ 0.11	:37.0	196.4± 50.0	:7.28	21.32± 8.10	:4.34E-08
15.32:18.03	CPL2+BB	:0.07	$-1.05\pm$ 0.07	:52.0	284.02± 52.6	:7.26E-08	$1.36\times10^{-6}\pm6.90\times10^{-8}$	:0.08
18.03:20.08	CPL2+BB	:0.08	$-1.09\pm$ 0.08	:76.4	329.6± 82.1	:6.91	22.72± 7.62	:7.58E-08
20.08:21.35	Band+BB	:0.04	$-0.83\pm$ 0.04	:17.0	233.60± 17.0	:8.36E-08	$5.89\times10^{-6}\pm7.87\times10^{-8}$	:0.03

T_{start}:T_{end}	Model	S/N	α	E_p (keV)	kT (keV)	F_p (erg $s^{-1}cm^{-2}$)	F_{BB} (erg $s^{-1}cm^{-2}$)	BIC
21.35:21.91	CPL2+BB	0.03	$-0.93\pm$ 0.03	:26.0	360.86± 26.0	:1.89E-07	$9.50\times 10^{-6}\pm 1.83\times 10^{-7}$	:_
21.91:22.41	CPL2+BB	0.05	$-0.97\pm$ 0.03	:64.5	481.0± 47.5	:5.15	27.13± 4.55	:1.78E-07
22.41:23.41	CPL2+BB	0.03	$-0.91\pm$ 0.03	:26.0	389.18± 26.0	:2.16E-07	$1.25\times 10^{-5}\pm 2.07\times 10^{-7}$	:0.03
23.41:23.72	CPL2+BB	0.04	$-0.93\pm$ 0.04	:51.6	435.0± 38.2	:2.11	31.10± 7.08	:1.99E-07
23.72:24.59	CPL2+BB	0.02	$-0.87\pm$ 0.02	:13.0	322.88± 13.0	:1.65E-07	$1.47\times 10^{-5}\pm 1.62\times 10^{-7}$	:0.02
24.59:25.87	Band+BB	0.04	$-0.86\pm$ 0.04	:15.0	220.87± 15.0	:2.23E-07	$1.02\times 10^{-5}\pm 2.19\times 10^{-7}$	:0.04
25.87:26.54	Band+BB	0.11	$-0.63\pm$ 0.20	:90.6	115.3± 31.4	:21.9	102.1± 56.4	:2.60E-07
26.54:27.39	CPL2+BB	0.04	$-0.81\pm$ 0.04	:11.0	196.32± 11.0	:1.21E-07	$9.09\times 10^{-6}\pm 1.11\times 10^{-7}$	:0.06
27.39:29.31	CPL2+BB	0.05	$-0.69\pm$ 0.05	:15.2	143.9± 15.2	:15.2	83.71± 9.14	:1.25E-07
29.31:31.01	CPL2+BB	0.04	$-0.77\pm$ 0.04	:11.0	185.0± 11.0	:9.43E-08	$1.05\times 10^{-5}\pm 9.60\times 10^{-8}$	:0.04
31.01:32.61	CPL2+BB	0.04	$-0.61\pm$ 0.04	:5.7	129.97± 5.7	:7.89	114.7± 7.79	:1.31E-07
32.61:33.45	CPL2+BB	0.05	$-0.83\pm$ 0.05	:10.0	148.44± 10.0	:1.23E-07	$8.06\times 10^{-6}\pm 1.72\times 10^{-8}$	:0.07
33.45:35.41	CPL2+BB	0.04	$-0.84\pm$ 0.04	:9.6	114.9± 9.6	:27.4	35.84± 20.9	:9.30E-08

T_{start}:T_{end}	Model	S/N	α	E_p (keV)	kT (keV)	F_p (erg $s^{-1}cm^{-2}$)	F_{BB} (erg $s^{-1}cm^{-2}$)	BIC
35.41:37.26	CPL2+BB	:0.04	$-0.89\pm$ 0.04	:3.4	$88.81\pm$ 3.4	:5.39E-08	$4.84\times10^{-6}\pm5.45\times10^{-8}$	:0.05
37.26:38.65	CPL2+BB	:0.05	$-0.85\pm$ 0.05	:5.5	$83.4\pm$ 5.5	:38.7	$56.74\pm$ 40.2	:6.14E-08
38.65:39.61	CPL2+BB	:0.05	$-1.08\pm$ 0.05	:2.86	$73.88\pm$ 2.86	:5.01E-08	$3.65\times10^{-6}\pm5.48\times10^{-8}$	:0.12
39.61:40.98	CPL2+BB	:0.09	$-1.01\pm$ 0.09	:12.6	$66.3\pm$ 12.6	:9.48	$28.62\pm$ 11.9	:5.55E-08
40.97:42.01	CPL2+BB	:0.05	$-1.08\pm$ 0.05	:2.73	$72.54\pm$ 2.63	:4.22E-08	5.6×10^{-8}	:5.46E-08
42.01:45.0	CPL2+BB	:0.05	$-1.29\pm$ 0.04	:8.21	$109.1\pm$ 8.21	:5.43E-08	$3.22\times10^{-6}\pm5.64\times10^{-8}$	:0.06

Note: Figure translations are in progress. See original paper for figures.