

Thermionic Analogy of Gamma-Ray Burst Emission from Core-Collapse Supernovae

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ABSTRACT

Gamma-ray bursts (GRBs) associated with core-collapse supernovae are among the most energetic events in the universe, yet their emission mechanisms remain incompletely understood. This study introduces a thermionic emission analogy by adapting the Richardson-Dushman equation to an astrophysical context. Using observational GRB data and estimated stellar core temperatures, the emission rate was reformulated and linearized to relate $\ln(R_{GRB}/T^2)$ to $1/T$. Linear regression yields an effective energy barrier of 1.245×10^{-13} J and an emission constant of 1.164. The results indicate that GRB emission is a temperature-dependent, barrier-limited process, offering a physical explanation for their rarity and variability. This analytical framework complements existing models and provides a simplified approach to understanding high-energy processes in stellar collapse.

Keywords:

Gamma-Ray Bursts,
Core-Collapse Supernovae,
Thermionic Emission
Analogy.

INTRODUCTION

Gamma-ray bursts (GRBs) are among the most energetic events in the universe and are closely associated with the core-collapse of massive stars and relativistic jet formation (Zhang *et al.*, 2021; Jerkstrand *et al.*, 2025). Previous studies have shown that jet propagation, angular momentum, magnetic fields, and stellar structure strongly influence whether a collapsing star produces a GRB (Janiuk *et al.*, 2023; Kumar & Zhang, 2021). Recent investigations further emphasize the importance of jet breakout, energy dissipation, and fallback accretion in determining GRB observability and variability (Gottlieb *et al.*, 2022; Bromberg *et al.*, 2021; Metzger, 2020; Siegel *et al.*, 2022). Multi-wavelength observations and simulations also reveal significant diversity in GRB energetics and environments (Margutti *et al.*, 2021; Laskar *et al.*, 2022).

Analytical studies, such as that of Obioha, Chineke and Okoro (2023), have likewise demonstrated the importance of simplified approaches in understanding GRB behaviour.

Despite these advances, most GRB models rely heavily on complex numerical simulations and often lack simple analytical expressions for emission rates. In condensed matter physics, the Richardson-Dushman equation describes thermionic emission as a temperature-dependent, barrier-limited process. Similar threshold behaviour has been proposed in GRB physics, where relativistic jets must overcome gravitational and

magnetic confinement before observable gamma-ray emission occurs (Beniamini *et al.*, 2020; Lazzati *et al.*, 2021). Motivated by the need for simplified theoretical frameworks (Levan *et al.*, 2023; Pe'er, 2025), this study develops a thermionic emission analogy for GRB production by adapting the Richardson-Dushman model to core-collapse supernovae in order to explain the rarity and variability of GRB emission within a unified thermodynamic framework.

MATERIALS AND METHODS

Study Design

This study adopts a quantitative, analytical, and semi-empirical research design aimed at investigating the emission rate of gamma-ray bursts (GRBs) from core-collapse supernovae using a thermionic emission analogy. The approach integrates observational astrophysical data with theoretical modeling, specifically adapting the Richardson-Dushman framework to describe GRB emission processes.

Materials

The materials used in this research consist of: GRB observational data given by Rui-Jing *et al.* (2012) to carry out some estimations. Published stellar evolution (Rui-Jing *et al.*, 2012) and core-collapse models used to estimate stellar core temperatures during collapse. Thus, relating the isotropic

energy E_{iso} to the internal radiation energy through an efficiency factor, η .

Computational software (Origin) for data processing, visualization, and regression analysis.

Data Collection Methods

GRB data were collected from publicly available astronomical databases (Rui-Jing *et al.*, 2012), focusing on GRB luminosity or photon flux (used as a proxy for emission rate R_{GRB}).

Stellar core temperatures, T were estimated using established theoretical models of massive star collapse, drawing from recent literature on supernova simulations and progenitor structure. Where direct measurements were unavailable, temperature values were inferred from energy scales and collapse dynamics reported in the literature.

Model Formulation

The GRB emission rate was modeled using an adapted form of the Richardson-Dushman equation (Modinos, 2020):

$$R_{\text{GRB}} = AT^2 e^{-E_b/kT} \quad (1)$$

where:

R_{GRB} is the GRB emission rate, T is the stellar core temperature, E_b is the effective jet escape energy, A is the emission constant and k is Boltzmann constant.

To facilitate analysis, the equation was linearized:

$$\ln\left(\frac{R_{\text{GRB}}}{T^2}\right) = \ln A - \frac{E_b}{k}\left(\frac{1}{T}\right) \quad (2)$$

Data Analysis Procedure

The GRB emission rate was approximated by the isotropic luminosity, defined as the ratio of isotropic energy to burst duration, $R_{\text{GRB}} \approx \frac{E_{\text{iso}}}{\Delta t}$ (Kumar & Zhang, 2021; Piran, 2021).

Following the radiation energy density relation $E = aT^4V$ (Rybicki & Lightman, 2004), and introducing an efficiency factor to account for partial conversion of internal energy into gamma-ray emission (Beniamini & Piran, 2020), the isotropic energy (E_{iso}) became:

$$E_{\text{iso}} = \eta aT^4V \quad (3)$$

where:

Efficiency factor, $\eta = 0.1$ (commonly used for high efficiency).

Radiation constant, $a = 7.56 \times 10^{-16} \text{Jm}^{-3}\text{K}^{-4}$ and $1 \text{erg} = 10^{-7}\text{J}$.

Volume of emission region, $V = \frac{4}{3}\pi R^3$ (for stellar core, $R \approx 10^7\text{m}$).

That is: $V = \frac{4}{3} \times 3.142 \times (10^7)^3 = 4.19 \times 10^{21}\text{m}^3$

Thus:

$$T = \sqrt[4]{\left(\frac{E_{\text{iso}}}{\eta aV}\right)} = \sqrt[4]{\left(\frac{E_{\text{iso}}}{0.1 \times (7.56 \times 10^{-16}) \times (4.19 \times 10^{21})}\right)} = \frac{\sqrt[4]{E_{\text{iso}}}}{(23.724)} \quad (4)$$

For each GRB dataset, the quantity: $\ln\left(\frac{R_{\text{GRB}}}{T^2}\right)$ was computed using the estimated temperature values. To transform the independent variable, reciprocal of temperature was calculated: $\frac{1}{T}$.

For graphical analysis, a plot of $\ln\left(\frac{R_{\text{GRB}}}{T^2}\right)$ against $\frac{1}{T}$ was generated to examine the linear relationship predicted by the model.

Linear regression was applied to the plotted data to determine:

Slope = $-\frac{E_b}{k}$ and Intercept = $\ln A$.

From the slope and intercept, the effective energy barrier E_b was calculated and the emission constant A was determined.

RESULTS AND DISCUSSION

Table 1: Estimates of the GRB emission rate, R_{GRB} and Stellar core temperature T using GRBs observational data

E_{iso} ($\times 10^{44}$) (J)	t (s)	$R_{\text{GRB}} = \frac{E_{\text{iso}}}{\Delta t}$ ($\times 10^{38}$) (J/s)	$T = \frac{\sqrt[4]{E_{\text{iso}}}}{(23.724)}$ (K)	T^2 ($\times 10^{19}$) (K ²)	$\ln\left(\frac{R_{\text{GRB}}}{T^2}\right)$ ($\text{Js}^{-1}\text{K}^{-2}$)	$\frac{1}{T}$ ($\times 10^{-10}$) (K ⁻¹)
8.25	2592000	3.183	7143738881.05	5.103	43.277	1.4
272	224640	1211	17118050791.4	29.30	47.471	0.6
67.2	336960	199.4	12068530793.7	14.56	46.367	0.8
1945	216000	9005	27992519283.3	78.36	48.493	0.4
182	110592	1646	15482102258.9	23.97	45.676	0.6
298	103680	2874	17513225942.8	30.67	48.289	0.6
655	138240	4738	21324183429	45.47	48.395	0.5
57.7	673920	85.62	11617322293.2	13.50	45.596	0.9
95.3	2592000	36.77	13169985893.9	17.34	44.501	0.8
200	164160	1218	15851471476.5	25.13	47.630	0.6
1383	89856	15390	25705001270.4	66.07	49.200	0.4

13.8	3412800	4.044	8124223383.28	6.600	43.259	1.2
117	177120	660.6	13863042353.7	19.22	47.286	0.7
227	293760	772.7	16361327916.7	26.77	47.112	0.6
114	189216	602.5	13773309209.7	18.97	47.207	0.7
1701	42336	40180	27069994220.1	73.28	50.056	0.4
58.9	682560	86.29	11677258877.1	13.64	45.594	0.9
98.9	100224	986.8	13292637382.3	17.67	47.772	0.8
350	77760	4501	18231781011.1	33.24	48.657	0.5
16.8	41040	409.4	8533739963.16	7.282	47.778	1.2
13.2	239328	55.15	8034439178.34	6.455	45.894	1.2
21.0	17280	1215	9023331406.72	8.142	48.754	1.1
67.4	309312	217.9	12077500350.8	14.59	46.452	0.8
17.6	30240	582.0	8633566760.12	7.454	48.107	1.2
69.6	64800	1074	12174871735.6	14.82	48.032	0.8
89.9	170208	528.2	12979322021.8	16.85	47.194	0.8
0.991	1728	573.5	4205624541.11	1.769	49.530	2.4
174	63072	2759	15309090722.4	23.44	48.517	0.7
22.6	21600	1046	9190501164.73	8.447	48.568	1.1
37.0	9504	3893	10395910110.3	10.81	49.635	1.0
184	102816	1790	15524461347.7	24.10	48.057	0.6
163	1728000	94.33	15061179543	22.68	45.174	0.7
0.242	47520	5.093	2956418601.36	0.874	45.512	3.4
2267	311040	7288	29085394897.7	84.60	48.205	0.3
56.5	5184	10900	11556443400.1	13.36	50.453	0.9
0.969	217728	4.451	4182086669.64	1.749	44.683	2.4
362	267840	1352	18386083463.9	33.80	47.438	0.5
75.9	80352	944.6	12441493832.7	15.48	47.860	0.8
81.4	50976	1597	12661005162.2	16.03	48.351	0.8
4.46	472608	9.437	6125560016.52	3.752	44.671	1.6
92.3	53568	1723	13065093133.1	17.07	48.363	0.8
11.9	68256	174.3	7828865374.56	6.129	47.097	1.3
57.9	54432	1064	11627376238	13.52	48.115	0.9
569	35424	16060	20586861901.2	42.38	49.687	0.5
0.008	115776	0.0691	1260621127.31	0.159	42.916	7.9
144	23328	6173	14601676003.8	21.32	49.417	0.7
63.7	213408	298.5	11908222556.7	14.18	46.796	0.8
43.6	22464	1941	10831377864.9	11.73	48.858	0.9
2.04	134784	15.14	5037552978.17	2.538	45.535	2.0
79.9	1500768	53.24	12602269984.2	15.88	44.959	0.8
109	11232	9704	13619736616.9	18.55	50.009	0.7
4.70	2276640	2.064	6206354082.03	3.852	43.125	1.6
88.7	59616	1488	12935790982.6	16.73	48.237	0.8
138	17280	7986	14447139165.1	20.87	49.696	0.7
101	1728	58450	13362644915.4	17.86	51.843	0.7
11.5	9504	1210	7762230673.83	6.025	49.051	1.3
119	5184	22960	13921910099.6	19.38	50.827	0.7
280	38016	7365	17242553908.4	29.73	49.261	0.6
108	100224	1078	13588390640.2	18.46	47.816	0.7
3.66	12096	302.6	5830185271.62	3.399	48.238	1.7
88.8	132192	671.8	12939435381.1	16.74	47.441	0.8
13.2	488160	27.04	8034439178.34	6.455	45.182	1.2
115	30240	3803	13803414983.2	19.05	49.045	0.7
124	50976	2433	14065899365.5	19.78	48.561	0.7
9.25	106272	87.04	7351018535.58	5.404	46.529	1.4
19.2	1037	18510	8823428927.58	7.785	51.523	1.1
365	10368	35200	18424058365.3	33.94	50.693	0.5

17.3	11232	1540	8596538458.31	7.390	49.089	1.2
206	41472	4967	15969042978.2	25.50	49.021	0.6
1.22	88992	13.71	4429982823.34	1.962	45.693	2.3
19.1	330912	57.72	8811917580.3	7.765	45.755	1.1
34.3	74304	461.6	10200832458.6	10.41	47.541	1.0
1173	3456	339400	24668150402.4	60.85	52.376	0.4
3722	2401920	1550	32923513591	108.4	46.409	0.3
100	1589760	62.90	13329445541.1	17.77	45.013	0.8
2972	743040	4000	31122486405.6	96.86	47.470	0.3
1808	950400	1902	27486009430.9	75.55	46.975	0.4

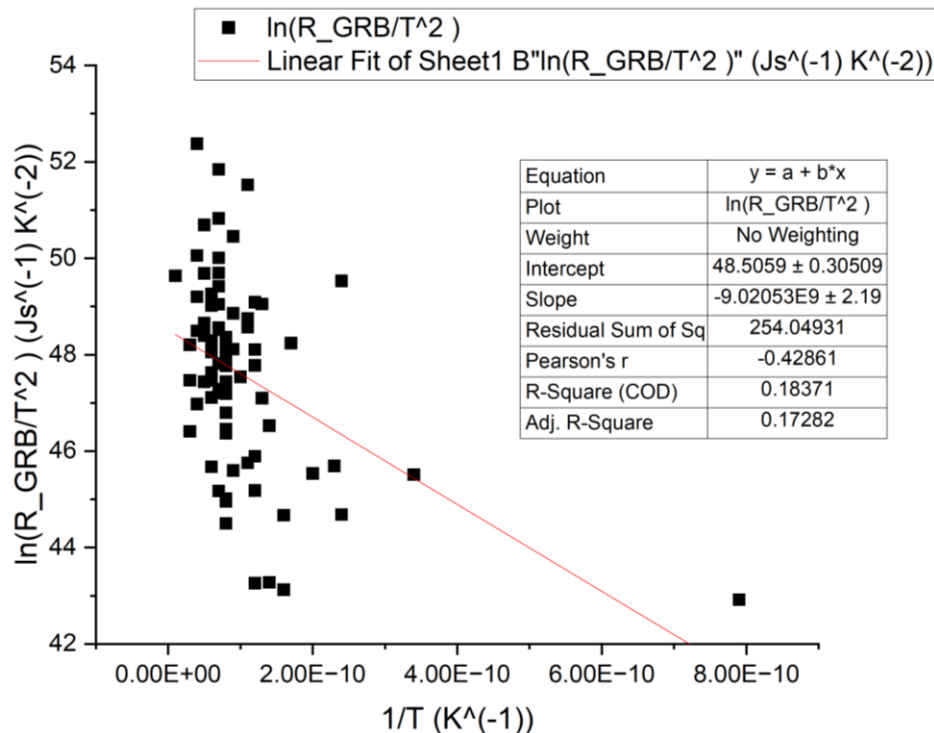


Figure 1: Plot of $\ln\left(\frac{R_{GRB}}{T^2}\right)$ against $\frac{1}{T}$.

From the plot in figure 1, the equation of a straight line becomes:

$$\ln\left(\frac{R_{GRB}}{T^2}\right) = \ln A - \frac{E_b}{k} \left(\frac{1}{T}\right) \quad (5i)$$

$$\ln\left(\frac{R_{GRB}}{T^2}\right) = 48.506 - (9.021 \times 10^9) \left(\frac{1}{T}\right) \quad (5ii)$$

To get the effective energy barrier E_b , we say:

$$\frac{E_b}{k} = 9.021 \times 10^9 \quad (6)$$

$$E_b = k \times (9.021 \times 10^9)$$

$$E_b = (1.38 \times 10^{-23}) \times (9.021 \times 10^9)$$

$$\therefore E_b = 1.245 \times 10^{-13} \text{ J}$$

To get the emission constant A , we say:

$$\ln A = 48.506 \quad (7)$$

$$\therefore A = e^{48.506} = 1.164$$

Discussion

The results of this study indicate that gamma-ray burst (GRB) emission from core-collapse supernovae can be

described as a temperature-dependent, barrier-limited process within a thermionic emission framework. The linear relationship obtained from the plot of $\ln(R_{GRB}/T^2)$ against $1/T$ supports the adapted Richardson-Dushman model and suggests that observable GRB emission occurs only when the collapsing stellar system overcomes a critical energy threshold.

The derived effective energy barrier, $E_b \sim 1.245 \times 10^{-13} \text{ J}$, is consistent with the extreme energetic conditions associated with relativistic jet breakout during stellar collapse. This interpretation agrees with the findings of Gottlieb, Nakar and Piran (2022), who showed that successful jet propagation through the stellar envelope is essential for GRB production. Similarly, Bromberg, Nakar and Piran (2021) emphasized that jet breakout conditions strongly determine GRB observability.

The emission constant, $A \approx 1.164$, reflects the efficiency of converting internal stellar energy into gamma-ray radiation. This is consistent with the work of Beniamini and Piran (2020), who demonstrated that GRB emission efficiency depends strongly on energy dissipation and jet dynamics. The strong sensitivity of the emission rate to temperature observed in this study also supports magnetar-driven and accretion-powered GRB models proposed by Metzger (2020).

Although the present approach simplifies the detailed hydrodynamic processes involved in stellar collapse, it provides a useful analytical framework that complements existing numerical simulations. Overall, the agreement between the present findings and previous theoretical studies suggests that the thermionic analogy captures an important aspect of GRB emission physics and offers a simplified explanation for the rarity and variability of GRBs.

CONCLUSION

This study demonstrates that gamma-ray burst emission from core-collapse supernovae can be described using a thermionic emission analogy. The results show that GRB production is a temperature-dependent, barrier-limited process, with the derived energy barrier and emission constant providing insight into the conditions required for emission. This framework offers a simple analytical approach that complements existing models and helps explain the rarity and variability of GRBs.

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