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Investigating the Effect of Gamma-ray Burst on the Agricultural Soil Temperature

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Gamma-ray bursts (GRBs) are immensely energetic explosions that have been observed in distant galaxies. This signatures from distant stars helps in carrying out spatial mapping of physical parameters related to soil properties, such as soil temperature. In investigating the effect of gamma-ray burst on the agricultural soil temperature, we used gamma-ray bursts (GRBs) data collected for some period of time to carry out some estimations. Linear regression analysis was carried out using the soil temperature T and the GRBs arrival time, t. There is an exponential relationship between temperature and time as the soil is heated. This depicts an exponential curve that was fitted into a line; and the slope at any point on the line gives the rate of cooling, k which is a determining factor for the time it takes for the soil to adjust between its high and low temperature.

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The thermal flux which relates to soil temperature is expected to decay at late times. The cooling rate reflects the degree of fall of temperature with time; and the higher the cooling rate, the shorter the time it takes for the soil to readjust its temperature between the upper and the lower ranges of thermal states. Thus the role of gamma-ray bursts in the management of agro-ecosystem is now becoming a reality.

Keywords: Soil temperature; gamma-ray burst; thermal flux.

1. INTRODUCTION

"Soil temperature is one of the most critical factors that influence important physical, chemical and biological processes in soil and plant science. Soil hydraulic properties are affected by soil temperature" [1]. "Bacterial growth and plant production are both strongly temperature dependent, so also are organic matter decomposition and mineralization. Soil temperature affects plant growth first during seed germination, although seeds of different plants vary in their ability to germinate at low temperatures, all species show a marked decrease in germination rate in soils with low surface temperatures. The germination rate will increase significantly with temperature up to a certain point, above which the rate falls off again" [2].

"It is impossible for the plants to evade from the unfavourable environmental conditions prevailing due to various abiotic stresses like heat, temperature and high radiance amongst many others. These abiotic stresses disrupt plant growth and limit crop productivity to a large extent globally. Massive amount of pertinent researches have been done in the last few decades regarding utilization of 'gamma rays' for improvement in traits, and management of agroecosystem by developing superior quality crops/germplasms. A better understanding of tolerance mechanisms induced by gamma rays will help in improving crop productivity under stress conditions. However, the potential mechanisms involved in this are still indefinable" [3].

"It was argued that gamma ray bursts are among the most dangerous astrophysical sources for biotic life and may exert evolutionary pressure on possible life forms in the universe. Their radiation can be directly lethal for biota or induce extinction by removing most of the protective atmospheric ozone layer on terrestrial planets" [4].

"Gamma-ray burst (GRBs) and its relationship to agricultural soil temperature form a basis of this research for investigating the effect of gamma-ray bursts on agricultural soil. Gamma-ray spectrometry is a fast and cost-efficient tool for carrying out spatial mapping of physical parameters related to soil properties" [5].

"In discussing the thermal emission in the early afterglow of gamma-ray bursts from their interaction with supernova (SN) ejecta, it was proposed that this thermal component is produced by the interaction of the GRB outflow with part of the SN ejecta, which is accelerated and heated" [6].

However, GRBs are highly variable in spectrum and duration. Recent observations indicate that short ($\sim$0.1s) burst GRBs, which have harder spectra, may be sufficiently abundant at low redshift that they may offer an additional significant effect. A much longer timescale is associated with shock breakout luminosity observed in the soft X-ray ($\sim 10^3$s) and UV ($\sim 10^5$s) emission and radioactive decay gamma-ray line radiation emitted during the light-curve phase of supernovae ($\sim 10^7$s) [7].

"In discussing 'guidelines on soil and vegetation sampling for radiological monitoring', the impacts of discharges of radionuclides to the environment were assessed by means of environmental monitoring, of which an obligatory component was the sampling of soil and vegetation" [8].

"On the modeling of potential effects of Gamma Ray Bursts on Phanerozoic Earth, there was a focus on global biospheric effects of ozone depletion and how a first modeling of the spectral reduction of light by NO_2 formed in the stratosphere. Illustration was done on the current complexities involved in the prediction of how terrestrial ecosystems would respond to this kind of burst. The researchers concluded that more field and laboratory data will be needed to reach even moderate accuracy in this modeling" [9].

From another work, "the temperature of the thermal component of GRBs at different time bins shows a clear "broken power law" with

$T(t) \sim t^{0.25}$ before $t_{brk} \sim 3$s, and $T(t) \sim t^{0.67}$ at later times" [10].

"In analyzing the theoretical implications of thermal emission from gamma-ray bursts, a probability density function $P(r, \theta)$ was used to describe photon escape at radius r and angle θ. It was shown that the thermal flux is expected to decay at late times as $F_{BB} \sim t^{-2}$, and the observed temperature decays as $T \sim t^{-\alpha}$, with $\alpha \sim {}^{1}/_{2} - {}^{2}/_{3}$. The analysis showed evidence for a thermal emission component that accompanies the emission during the prompt phase of GRBs" [11].

"In the prediction of soil temperature at various depths using a mathematical model, group of scientists modeled the annual soil temperature cycles with fairly good accuracy. Differences in the measured and predicted soil temperatures were determined by them at annual levels at depths 0cm (top soil), 10cm, 30cm and 50cm. For the annual cycle, the absolute errors ranged from 0.5°C to 7.8°C with an average of 2.7°C at the soil surface (0cm). At the 10cm depth, the errors ranged from 0.1°C to 4.5°C with an average value of 2.0°C. At the 30cm depth, the absolute errors ranged from 0.05°C to 2.9°C with an average of 1.7°C. The highest average absolute error was 2.7°C while the lowest average absolute error was 1.7°C" [12].

A research was made on "the Cooling behavior of thermal pulses in gamma-ray bursts. The discussion based on gamma-ray bursts (GRBs) that have very hard spectra. It was found that the pulses are consistent with a thermal, black-body radiation throughout their duration and that the temperature can be well described by a broken power-law as a function of time, with an initially constant or weak decay ($\sim$ 100 keV)" [13].

Other researchers continued with their previous work "on the potential short-term influence of a gamma ray bursts on Earth's biosphere, focusing on the only important short-term effect on life: the ultraviolet flash which occurs as a result of the retransmission of the γ radiation through the atmosphere. Thus, in this work they calculated the ultraviolet irradiances penetrating the first hundred meters of the water column" [14].

"Measurements of gamma radiation level and the water percentage of the top soil were also made at each site at different times of the year by other scientists. The data obtained throughout the whole year obeys a power law showing a decrease of gamma ray count per second with increase in top soil percentage water (% water)" [15].

2. MATERIALS AND METHODS

2.1 Sources of Data

We extracted gamma-ray burst data from the work of Rui-Jing et al. [16] which helped in carrying out some estimations.

2.2 Materials Used

i. Gamma-Ray Burst Data.

ii. The work of Oyewole et al. (2018):

$$T(z,t) = T_a + A_{z_a} sin\left[\frac{2\pi(t-t_0)}{365\ days}\right] \quad (1)$$

$$A_{z_a} = 3.4e^{-0.00446z} \quad (2)$$

iii. Stefan's law:

$$T_a = \left(\frac{L_E}{\sigma}\right)^{1/4} = \frac{\sqrt[4]{L_E}}{\sqrt[4]{(5.7\times10^{-8})}} = \frac{\sqrt[4]{L_E}}{0.0155} \quad (3)$$

where,

L_E is the luminous intensity (luminosity) of the gamma-ray burst.

$\sigma = 5.7 \times 10^{-8} Wm^{-2}K^{-4}$ is the Stefan's constant.

T_a is the temperature of the radiating body.

$T(z,t)$ is the soil temperature at time, t and soil depth z.

$A_{z_a} = 3.4e^{-0.00446z}$ is the amplitude of the annual temperature wave at soil depth z.

Soil depth, $z = 0.3m$ for cassava planting.

t is the GRBs arrival time.

$t_0 = 2592000$ is the time lag from the starting date (selected as the time for the first occurrence of GRBs).

2.3 Method of Data Analysis

The GRBs data were collected for some period of time to help carry out some estimations. The soil temperature $T(z,t)$ at time, t and soil depth z was extracted using the work of Oyewole et al. (2018); where T_a is the temperature of the radiating body (GRBs) gotten from Stefan's law.

Linear regression analysis was carried out using the soil temperature T and the GRBs arrival time t. This gave us a straight line equation of the form: $T = -2 \times 10^{-7}t + 2.1742$.

Thus, an exponential form of the equation was obtained: $T = 149.35e^{-(2\times10^{-7})t}$. This depicts that the exponential curve can be fitted into a line; and the slope at any point on the line gives the rate of cooling, k which is a determining factor for the time it takes for the soil to adjust between its high and low temperature.

We further investigated how the thermal flux which relates to temperature is expected to decay at late times.

3. RESULTS

Table 1. Estimates of the average soil temperature (T_a) and its variation at varying time of arrival t using GRBs samples by Rui-Jing et al. [16]

S/N.	GRB	Time (t) Second	E_γ^c (Joule) $\times 10^{43}$	Luminosity $\left(\frac{dE}{dt}\right) = L_E$ $\times 10^{37}$	$T_{(z,t)}$ (K) $\times 10^{11}$
1.	970508	2592000	2.96	1.142	1.186
2.	970828	224640	6.31	28.089	2.641
3.	980703	336960	3.06	9.081	1.992
4.	990123	216000	21.10	97.685	3.607
5.	990510	110592	2.39	21.611	2.474
6.	990705	103680	3.93	37.905	2.847
7.	991216	138240	7.56	54.688	3.120
8.	000301C	673920	3.49	5.179	1.731
9.	000418	2592000	16.70	6.443	1.828
10.	000926	164160	3.10	18.884	2.392
11.	010222	89856	9.40	104.612	3.669
12.	010921	3412800	6.38	1.869	1.341
13.	011211	177120	1.99	11.235	2.100
14.	020124	293760	3.92	13.344	2.193
15.	020405	189216	2.99	15.802	2.287
16.	020813	42336	6.61	156.132	4.055
17.	021004	682560	3.41	4.996	1.715
18.	030226	100224	1.23	12.273	2.147
19.	030328	77760	2.95	37.937	2.847
20.	030329	41040	0.36	8.772	1.974
21.	030492	239328	0.35	1.462	1.262
22.	041006	17280	0.14	8.102	1.936
23.	050315	309312	1.95	6.304	1.818
24.	050318	30240	0.13	4.299	1.652
25.	050319	64800	0.50	7.716	1.912
26.	050408	170208	1.77	10.399	2.060
27.	050416A	1728	0.002	1.157	1.190
28.	050505	63072	0.74	11.733	2.123
29.	050525A	21600	0.16	7.407	1.893
30.	050802	9504	0.08	8.418	1.954
31.	050814	102816	1.11	10.796	2.080
32.	050820A	1728000	13.10	7.581	1.904
33.	050826	47520	0.01	0.210	0.777
34.	050904	311040	13.10	42.117	2.923
35.	050922C	5184	0.08	15.432	2.274
36.	051016B	217728	0.07	0.322	0.864
37.	051022	267840	10.20	38.082	2.850

S/N.	GRB	Time (t) Second	E_{γ}^{c} (Joule) $\times 10^{43}$	Luminosity $\left(\frac{dE}{dt}\right) = L_E$ $\times 10^{37}$	$T_{(z,t)}$ (K) $\times 10^{11}$
38.	051109A	80352	0.84	10.454	2.063
39.	051111	50976	0.68	13.340	2.193
40.	051221A	472608	0.55	1.164	1.192
41.	060115	53568	0.50	9.334	2.005
42.	060124	68256	0.17	2.491	1.441
43.	060206	54432	0.35	6.430	1.827
44.	060210	35424	1.23	34.722	2.785
45.	060218	115776	0.002	0.017	0.414
46.	060418	23328	0.24	10.288	2.055
47.	060526	213408	1.28	5.998	1.795
48.	060605	22464	0.16	7.123	1.874
49.	060614	134784	0.18	1.335	1.233
50.	060707	1500768	4.95	3.298	1.546
51.	060714	11232	0.22	19.587	2.414
52.	060729	2276640	2.29	1.006	1.149
53.	060814	59616	1.01	16.942	2.328
54.	060906	17280	0.28	16.204	2.302
55.	060908	1728	0.04	23.148	2.516
56.	060926	9504	0.02	2.104	1.382
57.	060927	5184	0.07	13.503	2.199
58.	061121	38016	1.40	36.827	2.826
59.	070125	100224	1.49	14.867	2.253
60.	070208	12096	0.03	2.480	1.440
61.	070306	132192	1.56	11.801	2.126
62.	070318	488160	0.98	2.008	1.366
63.	070411	30240	0.37	12.235	2.146
64.	070508	50976	1.36	26.680	2.607
65.	070611	106272	0.22	2.070	1.376
66.	070714B	1037	0.02	19.290	2.404
67.	070721B	10368	0.43	41.474	2.911
68.	070810A	11232	0.05	4.452	1.667
69.	071003	41472	1.39	33.517	2.760
70.	071010A	88992	0.05	0.562	0.993
71.	071010B	330912	1.21	3.657	1.587
72.	071031	74304	0.36	4.845	1.702
73.	080319B	3456	0.80	231.481	4.475
74.	090323	2401920	114.00	47.462	3.011
75.	090328	1589760	7.29	4.586	1.679
76.	090902B	743040	62.70	84.383	3.477
77.	090926A	950400	53.20	55.976	3.138

From the plot of the soil temperature T against the time of arrival t from the GRBs, the equation of regression gives:

$$T = -2 \times 10^{-7} t + 2.1742 \quad (4)$$

Noting that the intercept, 2.1742 is equal to $\log 149.35$, equation (4) becomes:

$$T = -2 \times 10^{-7} t + \log 149.35 \quad (5)$$

Changing equation (5) to exponential form, we have:

$$T = 149.35 e^{-(2\times 10^{-7})t} \quad (6)$$

Equation (6) shows the exponential relationship between temperature and time as the soil is heated. It helps in giving insight on how the temperature of the medium varies in space and time.

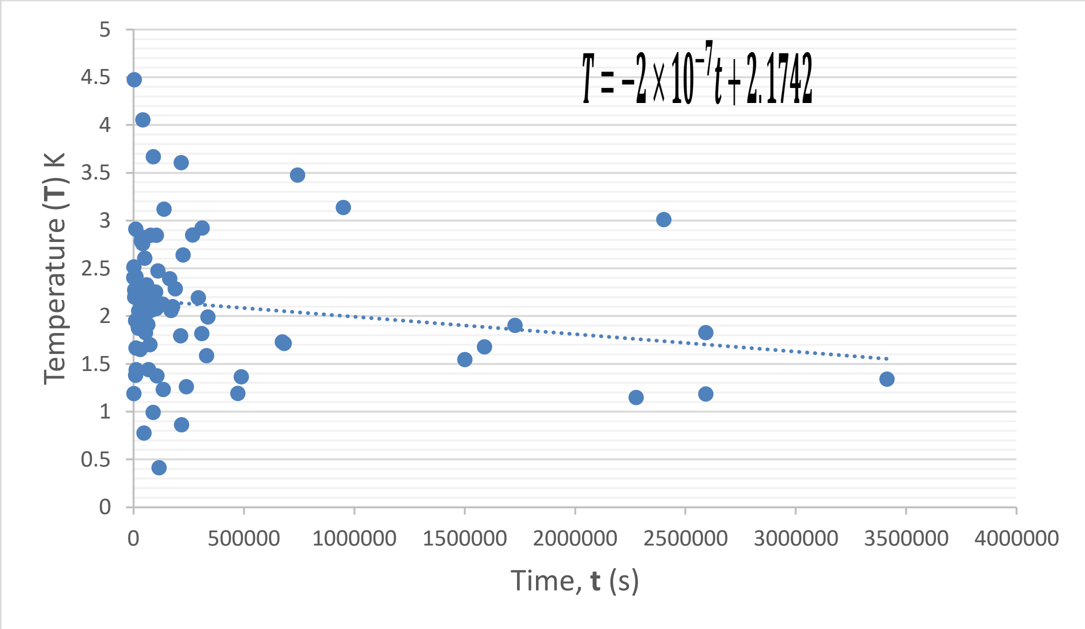

Fig. 1. Plot of the soil temperature T against the time of arrival t

4. DISCUSSION

Considering the cooling rate of the soil, the time rate of decrease of temperature is proportional to the difference in initial temperature before cooling and the surrounding. This is illustrated in equation (7) below:

$$\frac{dT}{dt} \propto (T - T_R)$$

$$\frac{dT}{dt} = -k(T - T_R) \tag{7}$$

where k is a constant known as cooling constant; and negative sign indicates that the temperature is decreasing.

T_R is the ambient temperature.

Separating variables in equation (7) and integrating from T_0 to T; and from 0 to t, we obtain:

$$\int_{T_0}^{T} \frac{dT}{T-T_R} = \int_0^t -kdt \tag{8}$$

$$\ln\left(\frac{T}{T_0}\right) = -kt \tag{9}$$

$$T = T_0 e^{-kt} \tag{10}$$

where $T_0 = T - T_R$.

From our research, a graph of falling soil temperature T against the time of arrival t from the GRBs gave an exponential curve that can be fitted into a line. The slope at any point on the line gives the rate of cooling, k which is a determining factor for the time it takes for the soil to adjust between its high and low temperature.

Looking closely to compare the parameters in equation (6) (equation of regression) and that of equation (10), we have the determining factor to be $k = 2 \times 10^{-7}$.

In the other hand, equation (10) helped to support the work of Asaf and Felix (2009) that thermal flux which relate to temperature is expected to decay at late times as:

$$t_{1/2} = \frac{\ln 2}{k} = \frac{0.693}{k} \tag{11}$$

Supporting their work, it has shown that the thermal flux is expected to decay at late times. It equally support that there is an evidence for a thermal emission component that accompanies the emission during the prompt phase of GRBs.

Also, the role of gamma-ray bursts in the management of agro-ecosystem is now becoming a reality unlike what Priya et al. (2022) said: “that the mechanism involved is still indefinable”.

Moreover, it has resolved to some extent the argument posed by Riccardo and Giancarlo (2023) that:

"gamma ray bursts are among the most dangerous astrophysical sources for biotic life".

5. CONCLUSION

The cooling rate reflects the degree of temperature reduction over time; the higher the cooling rate, the less time it takes for the soil to readjust its temperature between the upper and lower ranges of thermal states. Thus, the research support Newton's law of cooling, which states that the rate of loss of heat is proportional to the excess temperature over the surroundings.

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DATA AVAILABILITY

The date that support the findings of this research are available from the corresponding author (Aniezi, J. N.), upon reasonable request.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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