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# Exploration of Wien Displacement Law: A Fundamental Concept in Quantum Physics

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## Abstract

*This study explores the relationship between the temperature of a black body and the wavelength of the radiation it emits based on the Wien Displacement Law. This experiment collected maximum temperature and wavelength data using PhET simulation software and other supporting devices. The Wien Displacement Law states that the wavelength at which the maximum intensity of blackbody radiation occurs ($\lambda_{max}$) is inversely proportional to the absolute temperature of the object (T). To test this law, the temperature of the blackbody was set at various values in the simulation, and the resulting maximum wavelength was recorded. The linear regression method analyzed the data to determine the temperature and maximum wavelength relationship. The analysis results showed a linear relationship with a coefficient of determination $R^2 = 1$, indicating that the model fits the observed data well. The value of Wien's constant (b) calculated from the slope of the regression line is close to the theoretical value of 2.897 × 10-3 m.K, supporting the validity of the Wien Displacement Law. In conclusion, this study confirms that the maximum wavelength of electromagnetic radiation is inversely proportional to the absolute temperature of a blackbody, which agrees with the prediction of the Wien Displacement Law.*

***Keywords:*** *Exploration, Quantum Physics, Temperature, Wien Displacement Law, Wavelength*

## Introduction

The history of physical science has illustrated the evolution of human knowledge about the universe from simple views to complex understanding [1]. Physics, as a branch of natural science, has become an important milestone in the development of human thought [2]. This science developed rapidly in Persia, beginning with Aristotle, who introduced physics as part of philosophy [3]. It continues to emerge scientists who influenced the history of physics, such as Abdus Salam [4], Satyendranath Bose [5], Venkata Raman [6], Hideki Yukawa [7], and Leo Esaki [8]. Classical physics was pursued by scientists such as Roger Bacon [9], Nicolaus Copernicus [10], Galileo Galilei [11] and Isaac Newton [12]. Modern physics emerged in the early 20th century with scientists such as Max Planck. [13], Niels Bohr [14], Werner Heisenberg [15], Erwin Schrödinger [16], Albert Einstein [17] and Enrico Fermi [18]. The basic concepts that form the foundation of quantum physics have emerged from ongoing research and experimentation.

Physics, as the study of the properties of matter and energy, has evolved. From classical concepts such as Newton's laws of motion [19] to Einstein's theory of relativity [20], scientists continue to explore the universe's secrets. However, in the early 20th century, a new paradigm emerged that shook the foundations of physical science: quantum physics. Quantum physics brought a new understanding of the universe, where subatomic particles are dualistic, and their behavior cannot be

predicted with certainty [21]. The basic concepts of quantum physics introduced superposition, uncertainty, and entanglement. Superposition states that particles can be in multiple states simultaneously [22]. Heisenberg's uncertainty limits the extent to which we can know the position and momentum of a particle [23]. Entanglement is a phenomenon in which particles that are related to each other remain mutually affected even at large distances, being one of the main pillars of quantum physics [24]. Superposition refers to the ability of a quantum system to be in multiple states at once [25]. Entanglement creates a magical connection between quantum particles, where a change in the state of one particle will immediately affect the state of the associated particle [26].

Particle emissions from thermonuclear processes in the sun, or solar radiation, consist of electromagnetic radiation traveling through space through waves or particles. [27]. Sunlight has three wavelengths at the Earth's surface: visible light (400-700 nm), infrared light (more than 700 nm), and ultraviolet light (less than 400 nm) [28]. The distance from the sun, the strength of the radiation, the length of time the sun shines, and the influence of the atmosphere also affect the Earth's albedo, all impacting the quantity of radiation that reaches the Earth. [29].

The radiation-emitting props for heat transfer developed by [30] has produced wavelengths for red, green, and blue corresponding to the intervals of each color spectrum. The red, green, and blue wavelengths generated from this experiment are 740.254 nm, 499.638 nm, and 469.278 nm, respectively. Further testing is required as an inaccuracy of 23% was found in Wien's constant values obtained from manual experiments.

Wilhelm Wien originally proposed the Wien Displacement Law in 1893, which deals with how the temperature of a heated object affects the wavelength of the radiation it emits [31]. The knowledge of how blackbody radiation affects the wavelength of the radiation it emits is based on this law [32]. This rule states that as a black body's temperature increases, its radiation's wavelength will change to be shorter (higher frequency) [33]. Two main aspects of Wien's theory need to be known: Wien's Displacement Law and Wien's Law of Radiation.

Wien Displacement Law states that the wavelength at which the maximum intensity of blackbody radiation occurs ($\lambda_{max}$) is inversely proportional to the absolute temperature of the body ($T$) [34]. Mathematically, this law is expressed as:

$$\lambda_{\max} = \frac{b}{T} \tag{1}$$

Where $\lambda_{max}$ is the wavelength at which the maximum intensity occurs. $T$ is the absolute temperature in Kelvin. $b$ is Wien's constant, about 2.897×10-3 m.K [35].

Wien's Law of Radiation provides an equation for the distribution of the energy spectrum of blackbody radiation at various wavelengths at a given temperature. This was an early approach that Planck later refined with his theory of blackbody radiation [36]. Wien's Law of Radiation equation can be expressed as:

$$I(\lambda, T) = \frac{a}{\lambda^5} \exp\left(-\frac{b}{\lambda^5}\right) \tag{2}$$

Where $I(\lambda, T)$ is the intensity of radiation at wavelength $\lambda$ and temperature $T$. $a$ and $b$ are constants that depend on the physical properties of the radiation [37]. Wien's Law of Radiation works well at shorter wavelengths (ultraviolet light) but fails at longer wavelengths (infrared light), which was later improved by Planck's Law of Radiation [38].

By understanding the history of physical science, the evolution of quantum physics, the basic concepts of quantum physics, and Wien Displacement law, researchers can assemble a solid framework for further exploration of the interaction between energy and matter at the quantum level while bridging the gap between the macroscopic and microscopic worlds. This research focuses on an in-depth exploration of the relationship between temperature and wavelength of radiation emitted by a black body based on the Wien Displacement Law, as well as the mathematical proof of its linear equation stating that the maximum wavelength is inversely proportional to the absolute temperature. With a deep understanding of Wien Displacement law and quantum physics concepts, researchers can delve deeper into the complex interactions between energy and matter at the quantum level and explore the reality of the universe at the most miniature scale with a broader perspective.

## Methods

This research uses the leading equipment in the form of a laptop and is supported by software such as PhET simulation, Flash Player, and Java Run Time Environment. In addition, supporting instruments in the form of analysis sheets were used to determine Wien's constant. The method applied in this study uses a linear equation, namely the $y = ax + b$ model, where $x$ is the independent variable located on the horizontal axis, and $y$ is the dependent variable situated on the vertical axis. Parameter $a$ represents the slope of the line (gradient), while $b$ represents the intersection point of the straight line with the vertical axis.

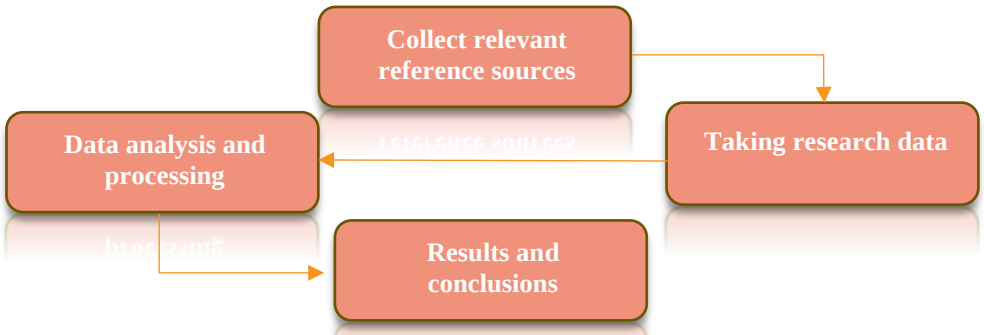



**Fig. 1.** Research Flow Chart

Fig. 1 outlines the comprehensive research process, beginning with the collection of relevant reference sources. We then meticulously collected data using PhET simulation to observe the relationship between blackbody temperature and its radiation wavelength. After the data collection, we conducted *a* thorough analysis and processing to determine the relationship. The results and conclusions were then compiled based on this rigorous analysis.

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$$a = \frac{N\sum(x_i y_i) - \sum x_i \sum y_i}{N\sum x_i^2 - \left(\sum x_i\right)^2} \quad (3)$$

$$b = \frac{\sum x_i^2 \Sigma y_i - \sum x_i \sum(x_i y_i)}{N\sum x_i^2 - \left(\sum x_i\right)^2} \quad (4)$$

Equations 3 and 4 show linear regression formulas precisely to calculate the coefficients $a$ and $b$ in the regression line equation $y = ax + b$. The formula for a is the slope of the line, and the formula for $b$ is the intercept of $y$ where $N$ is the number of data and xi is the value of the independent variable. $y_i$ is the value of the dependent variable, Σ which signifies summation.

## Results and Discussions

The temperature and wavelength spectrum associated with Wien Displacement law describes the fundamental relationship between the temperature of a hot body and the wavelength of the radiation it emits. This law states that the maximum wavelength of electromagnetic radiation emitted by a black body moves inversely with the body's absolute temperature. As the object's temperature increases, the radiation's maximum wavelength becomes shorter, thus moving the energy spectrum of the radiation in a higher direction. This concept is not only important in quantum physics and astronomy, but also has practical applications in the development of infrared sensors used in various fields of modern technology, such as night vision, remote temperature sensing, and thermal imaging. The temperature and wavelength spectrum in this study can be seen in Fig. 2.

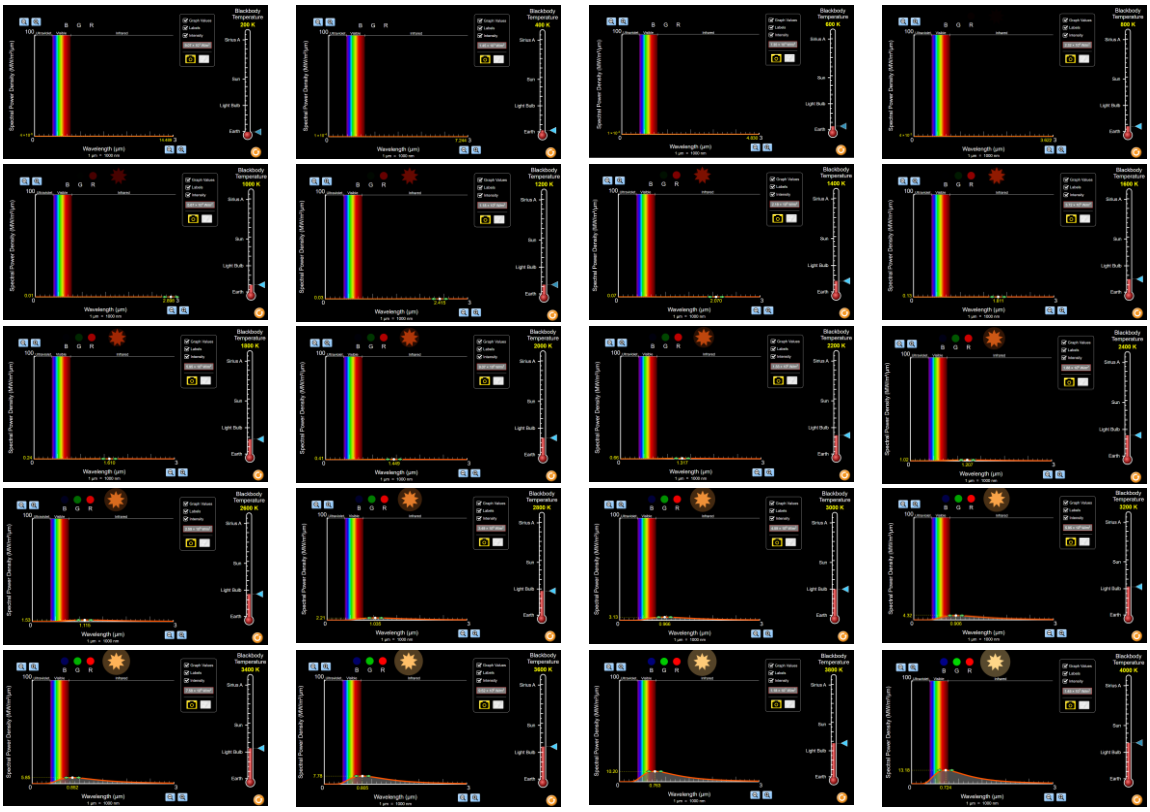


**Fig. 2.** Temperature and Wavelength Spectrum

The solar radiation spectrum in Fig. 2 shows a maximum intensity at 500 nm, corresponding to the yellow-green color of the Sun. This is consistent with the Wien Displacement Law, which states that the higher the temperature of an object, the shorter the wavelength at which the maximum radiation intensity occurs. The Sun's high surface temperature (5,500 K) causes its spectrum to be in the visible light range, which is crucial for life on Earth as it provides the necessary light for photosynthesis and vision. If the temperature were lower, the spectrum would shift to the infrared, like a red-hot iron.

**Table 1.** Temperature and Wavelength Data

| No. | *T* (K) | *λ* (m) |
|---|---|---|
| 1. | 200 | 0.000014489 |
| 2. | 400 | 0.000007244 |
| 3. | 600 | 0.00000483 |
| 4. | 800 | 0.000003622 |
| 5. | 1000 | 0.000002898 |
| 6. | 1200 | 0.000002415 |
| 7. | 1400 | 0.00000207 |
| 8. | 1600 | 0.000001811 |
| 9. | 1800 | 0.00000161 |
| 10. | 2000 | 0.000001449 |
| 11. | 2200 | 0.000001317 |
| 12. | 2400 | 0.000001207 |
| 13. | 2600 | 0.000001115 |
| 14. | 2800 | 0.000001035 |
| 15. | 3000 | 0.000000966 |
| 16. | 3200 | 0.000000906 |
| 17. | 3400 | 0.000000852 |
| 18. | 3600 | 0.000000805 |
| 19. | 3800 | 0.000000763 |
| 20. | 4000 | 0.000000724 |

Table 1 presents the temperature and wavelength data associated with Wien Displacement Law, illustrating the measured relationship between the temperature (*T*) of a hot body and the wavelength (*λ*) of its emitted radiation. The data shows that as the object's temperature increases from 200 K to 4000 K, the maximum wavelength of blackbody radiation tends to decrease from 0.000014489 m to 0.000000724 m.

**Table 2.** Trial Data

| i | x | y | xy | $x^2$ | y estimasi | $(y\text{-yestimasi})^2$ |
|---|---|---|---|---|---|---|
| | 1/T | l (m) | | | | |
| 1 | 0,005 | 0,000014489 | 7,2445E-08 | 0,000025 | 1,45001E-05 | 1,22102E-16 |
| 2 | 0,0025 | 0,000007244 | 1,811E-08 | 0,00000625 | 7,25005E-06 | 3,66025E-17 |
| 3 | 0,001667 | 0,00000483 | 8,05E-09 | 2,77778E-06 | 4,83338E-06 | 1,14469E-17 |
| 4 | 0,00125 | 0,000003622 | 4,5275E-09 | 1,5625E-06 | 3,62505E-06 | 9,3025E-18 |
| 5 | 0.001 | 0.000002898 | 2.898E-09 | 0.000001 | 2.90005E-06 | 4.2025E-18 |
| 6 | 0.000833 | 0.000002415 | 2.0125E-09 | 6.94444E-07 | 2.41672E-06 | 2.94694E-18 |
| 7 | 0.000714 | 0.00000207 | 1.47857E-09 | 5.10204E-07 | 2.07148E-06 | 2.18617E-18 |
| 8 | 0.000625 | 0.000001811 | 1.13188E-09 | 3.90625E-07 | 1.81255E-06 | 2.4025E-18 |
| 9 | 0.000556 | 0.00000161 | 8.94444E-10 | 3.08642E-07 | 1.61116E-06 | 1.34818E-18 |
| 10 | 0.0005 | 0.000001449 | 7.245E-10 | 0.00000025 | 1.45005E-06 | 1.1025E-18 |

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| | | | | | | |
|---|---|---|---|---|---|---|
| 11 | 0.000455 | 0.000001317 | 5.98636E-10 | 2.06612E-07 | 1.31823E-06 | 1.51738E-18 |
| 12 | 0.000417 | 0.000001207 | 5.02917E-10 | 1.73611E-07 | 1.20838E-06 | 1.91361E-18 |
| 13 | 0.000385 | 0.000001115 | 4.28846E-10 | 1.47929E-07 | 1.11543E-06 | 1.88891E-19 |
| 14 | 0.000357 | 0.000001035 | 3.69643E-10 | 1.27551E-07 | 1.03576E-06 | 5.84133E-19 |
| 15 | 0.000333 | 0.000000966 | 3.22E-10 | 1.11111E-07 | 9.66717E-07 | 5.13611E-19 |
| 16 | 0.000313 | 0.000000906 | 2.83125E-10 | 9.76563E-08 | 9.063E-07 | 9E-20 |
| 17 | 0.000294 | 0.000000852 | 2.50588E-10 | 8.65052E-08 | 8.52991E-07 | 9.82431E-19 |
| 18 | 0.000278 | 0.000000805 | 2.23611E-10 | 7.71605E-08 | 8.05606E-07 | 3.66698E-19 |
| 19 | 0.000263 | 0.000000763 | 2.00789E-10 | 6.92521E-08 | 7.63208E-07 | 4.32202E-20 |
| 20 | 0.00025 | 0.000000724 | 1.81E-10 | 6.25E-08 | 7.2505E-07 | 1.1025E-18 |
| Σ | 0.017989 | 0.000052128 | 1.15634E-07 | 3.99041E-05 | 5.21682E-05 | 2.00946E-16 |

Table 2 presents in-depth experimental results related to Wien Displacement law, focusing on the relationship between inverse temperature ($1/T$) and wavelength ($\lambda$) of blackbody radiation. The data collected shows that as the value of $1/T$ decreases from 0.005 to 0.00025, there is a measurable increase in the wavelength of the observed radiation from 0.000014489 m to 0.000000724 m. The mathematical analysis performed included the calculation of the product xy, the square of x, and an estimate of the obtained wavelength ($y$ estimate) based on Wien Displacement law model.

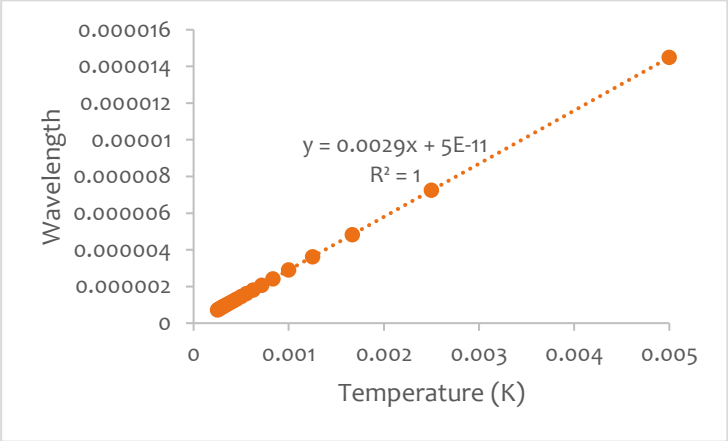



**Fig. 3.** Linear Regression Graph of Relationship Between Temperature and Wavelength

The linear regression graph in Fig. 3 shows the relationship between temperature (inverse of temperature, $1/T$) and the maximum wavelength ($\lambda$) associated with the Wien Displacement law. It depicts a regression line with the equation $y = 0.0029x + 5E\text{-}11$ and a coefficient of determination value of $R^2 = 1$, indicating a solid linear relationship between the two variables. The value of $R^2 = 1$ suggests that this regression model can explain the entire variability in the wavelength data based on the temperature variable. This result is consistent with the Wien Displacement law theory, which states that the maximum radiation wavelength is inversely proportional to the blackbody temperature.

This research delves into the fundamental relationship between the temperature of a hot body and the wavelength of the radiation it emits, as per the Wien Displacement Law. The results not only align strongly with theoretical principles but also validate the Wien Displacement Law, which states that the maximum wavelength of the radiation emitted by a black body is inversely proportional to the

absolute temperature of the body [39]. This validation provides a solid foundation for further exploration. The data in Table 1 and Table 2, along with the visualization of the solar radiation spectrum in Fig. 2 and the linear regression results in Fig. 3, all reinforce the robustness of this research.

Fig. 2 shows the spectrum of solar radiation with maximum intensity at a wavelength of about 500 nm, corresponding to the yellow-green color. The Sun's surface temperature, about 5,500 K, emits a spectrum in the visible light range, in agreement with the prediction of the Wien Displacement Law. This confirms that high temperatures produce radiation at shorter wavelengths, which can be observed as visible light [40]. conversely, if the Sun has a lower temperature, its spectrum will shift to the infrared region, like red-hot iron [41].

Table 1 provides empirical data illustrating the relationship between temperature and the maximum wavelength of emitted radiation. These data show a clear trend: with increasing temperature from 200 K to 4000 K, the maximum wavelength of blackbody radiation decreases from 0.000014489 m to 0.000000724 m. This provides quantitative evidence of how increasing temperature causes a shift in the radiation spectrum to shorter wavelengths by Wien's Law. This provides quantitative evidence of how increasing temperature causes a change in the radiation spectrum to shorter wavelengths by Wien Displacement Law [42].

Table 2 complements these findings by showing more detailed experimental results, focusing on the relationship between the inverse temperature ($1/T$) and blackbody radiation's wavelength ($\lambda$). As the value of $1/T$ decreases from 0.005 to 0.00025, the wavelength of the observed radiation increases from 0.000014489 m to 0.000000724 m. These data were analyzed using linear regression, which resulted in the equation $y = 0.0029x + 5E\text{-}11$ with a coefficient of determination $R^2 = 1$. A perfect $R^2$ value indicates that this regression model can fully explain the variability in the wavelength data based on the object's temperature. This confirms the validity of the Wien Displacement Law in explaining the relationship between temperature and wavelength of maximum radiation.

The linear regression graph in Fig. 3 shows a solid relationship between temperature (inverse temperature, $1/T$) and maximum wavelength ($\lambda$). The resulting regression line shows that any temperature change is inversely proportional to the change in the maximum radiation wavelength, which supports the theoretical model of the Wien Displacement Law. The $R^2 = 1$ value indicates that the empirical data fully matches the theoretical predictions, suggesting that there is no other variability not explained by the model.

The results of this study have broad implications in a variety of fields. In quantum physics and astronomy, understanding the distribution of the radiation spectrum is essential for interpreting the phenomena of the universe [43]. For example, in astrophysics, determining the temperature of stars through their radiation spectra allows scientists to study the nature and evolution of stars. Similarly, the analysis of Cosmic Microwave Background (CMB) radiation in cosmology, which uses the blackbody principle, helps understand the universe's initial conditions and supports the Big Bang Theory [44].

In addition to basic science applications, this research has a significant practical impact. In the development of infrared sensor technology, a deep understanding of the relationship between temperature and radiation wavelength enables the design of more accurate and efficient sensors.

Infrared sensors are used in various applications, including thermography, security, and environmental monitoring [45]. Using the Wien Displacement Law principle, these sensors can be calibrated to detect temperature with high precision.

This research is not just about theoretical principles; it has significant practical implications. In the materials industry, for instance, the control of thermal radiation can lead to improved energy efficiency in heating and cooling systems. Materials designed to emit or absorb radiation at specific wavelengths can be used to optimize thermal performance in various industrial applications [46]. Moreover, this research can inspire innovation in the renewable energy sector, such as in the design of more efficient solar panels by understanding the solar radiation spectrum in depth. These practical applications can inspire further research and development in these fields [47].

In the realm of education, this study provides concrete examples of how basic physics theories are applied in experiments and data analysis. It offers students a chance to see empirical evidence that supports the theory, making abstract concepts more tangible and engaging. The use of data visualization and in-depth analysis not only makes learning more effective but also sparks curiosity, motivating students to explore more about the world of physics. This educational value is a key aspect of the research, making it relevant and interesting to a wide audience.

Overall, this study reaffirms the validity of the Wien Displacement Law and shows how the relationship between temperature and wavelength of blackbody radiation can be applied in various scientific and technological fields. The findings strengthen our understanding of the fundamental principles of physics and open up opportunities for innovation in sensor technology, thermal materials, and other applications that utilize electromagnetic radiation. As such, this research is important from a theoretical standpoint and has a significant practical impact on everyday life. Continued research can develop new applications of this principle, especially in technology and materials science.

## Conclusion

This study successfully confirmed and illustrated the fundamental relationship between the temperature of a hot object and the wavelength of the radiation it emits by the Wien Displacement Law. The empirical data shows that an increase in temperature from 200 K to 4000 K causes a decrease in the maximum wavelength from 0.000014489 m to 0.000000724 m, with an $R^2$ value of 1, indicating a solid linear relationship between the temperature and wavelength variables. The spectrum of solar radiation that shows maximum intensity at a wavelength of 500 nm also strengthens the validity of this law by the theoretical prediction stating that the higher the temperature, the shorter the wavelength of the maximum emitted radiation. These results have essential implications in quantum physics and astronomy, as well as practical applications in developing infrared sensors and thermal material technologies. Various technological innovations can be generated by understanding and utilizing this relationship, improving efficiency and effectiveness in different scientific and industrial applications. The overall findings of this research strengthen our theoretical knowledge of the distribution of electromagnetic radiation and open up new opportunities for applying fundamental physics principles in modern technology.

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