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Radiation from Proxima Centauri Reaching Its Planet Proxima b

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Abstract

Recently, interest in the planet Proxima b has increased following indications that liquid water may be present there. The literature has reported measurement data for the radiation spectrum of the star Proxima Centauri as received by this planet, together with an estimate of an effective temperature (3050 K) of that radiation, obtained from the Stefan-Boltzmann law for blackbody surface emission. This approach relies on a heat-balance assumption and does not yield a physically meaningful temperature suitable for heat-transfer calculations. Moreover, the irregular shape of the measured spectrum shows that this radiation cannot be treated as originating from a blackbody surface. Therefore, in the present work, the temperature of this radiation (3255 K) was determined using Planck's law, based on the monochromatic radiation intensities at individual wavelengths. It was also shown that the temperature obtained in this way is ambiguous, representing only the minimal possible value. A further novelty of this study is the introduction of the most recent elements of thermodynamic analysis, specifically, the determination of the exergy of the radiation in question (693 W/m^2). The exergy-to-energy ratio for this radiation was found to be 0.893, in close agreement with the theoretical value of 0.9042. Furthermore, the energetic and exergetic emissivities of Proxima Centauri's surface were determined to be 0.6415 and 0.2019, respectively.

Keywords

Proxima Centauri, Proxima b, Surface Temperature, Surface Emissivity, Planck Formula, Radiation Exergy

1. Introduction

The presented work partly concerns the field of astrophysics and astronomy. This discipline seeks knowledge about the cosmos and primarily constructs a vast edifice of understanding as a scientific repository of rich information—meticulous, precise, and almost entirely free from even the smallest steps of generalized interpretation. It therefore preserves great caution so as not to damage the authenticity and freshness of the results of discovery. Technical thermodynamics, however, operates by interpreting nature through somewhat simplified models of natural phenomena, since such models give humanity the opportunity to practically utilize these phenomena by quantifying them, predicting their course, and enabling their control for human benefit.

From celestial bodies, we expect, above all, energy in the form of heat, received through radiation. Without introducing certain interpretative concepts in the form of simplifying models, it is difficult to consider quantitatively and qualitatively the exchange of energy through radiation in engineering problems. For this reason, we readily employ the concept of a radiating surface, to which we assign a thermodynamically active temperature and emissivity as a quantitative measure of its ability to emit radiation. Radiation is evaluated not only by its energy, but also by its entropy and the resulting exergy, which provides a quantitative assessment of the practical value of radiation for humanity; exergy indicates the possible amount of work that can be obtained. For example, the energy of radiation is often assessed by the exergy-to-energy ratio, which has a significance similar to the general efficiency of Carnot. Furthermore, the determination of a temperature better evaluates the direction of energy flow in complex systems and, for instance, provides the theoretical limit of temperature concentration of diluted radiation.

Of course, these conceptual models are in a sense scientific prosthesis, or working hypotheses, which describe phenomena with sufficient accuracy to satisfy human needs in utilizing nature. Examples of hypotheses of much greater importance include the interpretation of radiation either as an electromagnetic wave field or as a collection of photons. This article is therefore an attempt to connect engineering elements with knowledge in the field of astrophysics and astronomy.

This is about the Proxima Centauri (hereafter Proxima) and its planetary system as a gateway to habitability. The stellar parameters of Proxima used in this study are based on published values of mass, radius, and effective temperature [1]. Discovered in 1915, Proxima is a small red dwarf star with a mass of 12% and radius 14.6% that of the Sun, and a surface temperature of 2980 ± 80 K [2].

Red dwarfs (spectral type M stars) constitute the most numerous stellar populations in the Milky Way, accounting for an estimated 70% to 75% of all observable stellar objects [3]. They are the smallest celestial bodies capable of sustaining thermonuclear hydrogen fusion in their cores, although this process occurs much more slowly than in more massive stars due to lower internal temperatures and pressures.

Stars like the Sun burn only 10% of their total hydrogen fuel, while Proxima will use almost all its fuel. As a result, Proxima, which falls within the low-mass range of red dwarfs, has an extraordinarily long lifespan, with estimates reaching up to four trillion years. For the same reason, being in the low-mass range, Proxima is fully convective [3]. This means that heat and material inside Proxima circulate freely. Thus, the helium produced by the thermonuclear fusion of hydrogen is constantly remixed throughout the star, preventing helium buildup at the core.

Proxima Centauri hosts two confirmed exoplanets: Proxima b and Proxima d. A third candidate, Proxima c, remains unconfirmed due to disputed observational data. Of these, only Proxima b orbits within the star's habitable zone at a distance of about 7.253 million km, at a distance of 0.04848 astronomical units (AUs), just under 5% of the Earth-Sun distance [4]. According to our estimation, this places it about 189 times farther than the Moon is from Earth. Proxima b receives stellar flux of 950 W/m^2 [4]. A year later [5] quotes the total irradiance on Proxima b to be 877 ± 44 W/m^2. The upper limit to the orbital eccentricity of the exoplanet is less than 0.35 [6].

The Proxima Centauri system is gravitationally bound to the binary star system Alpha Centauri A and Alpha Centauri B, both of which have solar-like masses. Proxima Centauri completes a wide orbit around this binary pair over a period of roughly 547 thousand years, with its distance varying between 4.3 and 13 thousand AU [7]. Together, Alpha Centauri A, B, and C form the Alpha Centauri system, located in the constellation Centaurus, just 4.25 light-years from the Sun. Because Proxima Centauri is the closest of the three to our solar system, it is commonly referred to by its Latin name "Proxima", meaning "nearest". While Alpha Centauri A and B are visible to the naked eye, Proxima Centauri requires a telescope to be observed.

The bolometric luminosity of Proxima is 0.15% that of the Sun, which gives approximate total power output of 5.78×10^{23} W [5]. Of this, 85% is emitted at infrared wavelengths. Despite its low luminosity, Proxima is a highly active and variable star, frequently undergoing sudden increases in brightness due to large fluctuations in convective processes. These events include flares and coronal mass ejections originating near its numerous star spots, analogous to sunspots, which are localized contortions in the magnetic field caused by persistent convective plasma motion.

Proxima b completes an orbit around its host star in just 11.2 days [8] and is tidally locked [4], meaning the same hemisphere always faces Proxima Centauri, much like the Moon always shows the same face to Earth. The minimum mass of Proxima b is equal to 1.27 Earth masses [9]. The range of masses and radii for which a planet can reasonably be expected to be terrestrial has been studied in detail, thanks to planetary research from the *Kepler* mission [10]. They found that there is evidence of a density transition that occurs at ~1.5 - 2.0 Earth radii, whereby the composition of objects larger than this becomes dominated by volatile rather than rocky materials [8]. The probability that the planet has Earth's characteristics is ~84% [9].

It is hypothesized that Proxima b has an atmosphere at least as dense as Earth's, likely dominated by hydrogen and helium. Given its position within the habitable zone, the planet's average surface temperature may permit the existence of liquid water. This possibility has generated considerable interest among astronomers and astrobiologists, offering a rare opportunity to study the thermal dynamics, atmospheric composition, and electromagnetic irradiation of a potentially habitable exoplanet. Key areas of investigation include atmospheric pressure, heat distribution between the planet's bright and dark hemispheres (as it experiences no day-night cycle), and the mechanisms of radiative and thermal exchange with its surface.

The main contribution of this paper is the determination of the temperature of the radiation incident on the surface of Proxima b, along with an exergetic assessment of this radiation. A distinctive feature of this planet, in comparison with Earth, is its relatively low surface temperature (approximately −39˚C), which has a significant influence on the resulting exergy.

2. Proposed Methodology for Examination of the Star Temperature and Radiation

The analysis of the Sun's surface temperature [11] provides a foundation for developing a general methodology applicable to any star. This approach enables the determination of stellar surface temperature and the estimation of both radiation energy and exergy as the key parameters for engineering analyses of heat exchange involving stellar sources.

The methodology, previously applied successfully to the Sun, begins with minimal input: the star's diameter and its distance from a given planet. Although the surface temperature is initially unknown, the radiation spectrum of the star must be characterized by the monochromatic directional intensity i_λ, e.g., in W/(m^2·m·sr), as a function of wavelength λ (e.g., in nm). From the available spectral data, a representative range of wavelengths is selected to infer the actual temperature of the star's surface. Based on Planck's hypothesis, the temperature corresponding to the spectral intensity at each wavelength is computed, and the maximum of these values is interpreted as the star's minimum possible surface temperature. For instance, in the case of the Sun, this method yields a temperature of 7134 K. This actual temperature differs from the commonly used effective temperature.

Subsequently, the radiation energy of the star is determined by numerically integrating the area under the spectral intensity curve, yielding a value in W/(m^2·sr). Multiplying this area by the solid angle subtended by the star as seen from the planet provides the radiation constant (e.g., in W/m^2) relevant to that planetary location. For the Sun, the integrated spectral intensity of 10,079,300 W/(m^2·sr), when multiplied by the solid angle $2\pi \times 2.16 \times 10^{-5}$, results in a solar constant of approximately 1370 W/m^2.

The next step involves the application of Planck's hypothesis to derive the entropy L, W/(m^2·m·sr·K), of the radiation intensity. Analogous to the energy calculation, the total entropy of the star's radiation is obtained by integrating the area under the entropy curve. For the Sun, this yields a total entropy of 2263.3 W/(m^2·sr·K).

Given the known energy and entropy of stellar radiation, and assuming an ambient temperature T_0 at the planet's surface, the exergy of the radiation can be computed. For the Sun, relative to Earth with $T_0 = 300$ K, the radiation exergy is found to be 1282 W/m^2, which is 6.74% lower than the corresponding radiation energy.

Using the determined temperature of the star's surface, one can calculate the blackbody emission of energy, entropy, and exergy via the Stefan-Boltzmann law, Planck's formula, and Petela's exergy formula, respectively. The ratio of actual radiation energy to blackbody energy emission defines the energetic emissivity, while the ratio of actual exergy to blackbody exergy defines the exergetic emissivity. For the Sun, these values are 0.431 and 0.426, respectively.

The methodology outlined above is now applied to the case of Proxima.

3. Basic Equations and Terms

3.1. Concept of Star Surface

The calculation of radiative heat exchange between surfaces becomes comparatively straightforward when their thermal characteristics are represented using idealized or simplified models.

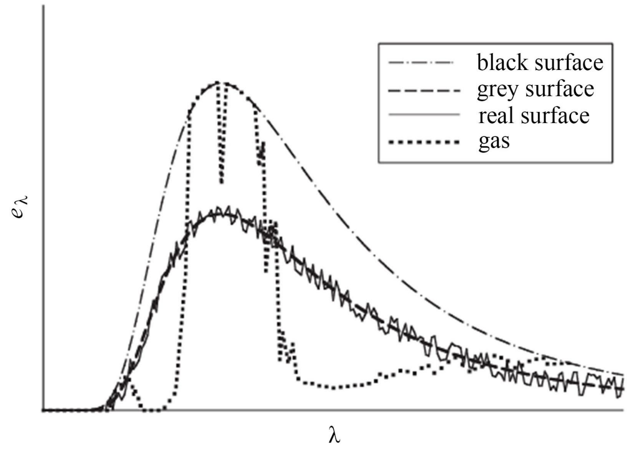

Figure 1. Examples of spectra of three surfaces: black, grey (at $\varepsilon = 0.6$), and real, compared to the spectrum of gas (H_2O), at the same temperature [12].

Figure 1 shows four examples of the different surface spectra for the same temperature. The largest and always the maximum values of the spectrum appear for the black surface (dashed-dotted line). The real surfaces (solid line) have the smaller values of the monochromatic emission, which can be represented by the regular averaged curve (dashed line) corresponding to the appropriately selected model of a perfectly gray surface with a constant value of emissivity ε. Thus, the spectra for the models of black and gray surfaces reach the maximum for the same wavelength. An entirely different type of spectrum can appear for a gas. The gas spectrum can be irregular (e.g., dotted line) so that application of the gray model is too inexact [12]. The emissivity of a solid surface determines the surface's ability measured by the rate at which black radiation is produced. It is worth emphasizing that it means, e.g., that the perfect gray surface emits black radiation in an amount determined by its emissivity.

The outward radiation of a gas body is governed by internal heat exchange phenomena, both convective and radiative [13]. This radiation originates from the entire volume, not merely from a surface. Stars are surrounded by an atmosphere, which may consist of low-temperature plasma [14]. Gas differs fundamentally from plasma: gas molecules are electrically neutral, and their thermal radiation arises solely from molecular motion and vibration. Gas emission is typically weak and depends on both temperature and molecular composition. Moreover, gases can absorb and emit radiation only at specific wavelengths.

Plasma, by contrast, is an ionized gas containing free electrons and ions. It can emit intense radiation across a broad spectral range, from radio waves to X-rays, and serves as a highly efficient source of radiation. For computational simplicity, the radiative interaction of a star with its surroundings, via the plasma envelope, can be modeled using an imaginary surface of a solid body with the same diameter as the star. This surface is assumed to have uniform temperature and a consistent spectral distribution across all points. For such a surface, one can define the emissivity ε, expressed as a percentage: the ratio of the actual radiative energy to that of an ideal blackbody surface. The emissivity of a blackbody is $\varepsilon = 1$ (100%). This ratio may be applied globally, to a specific wavelength, or to a defined spectral range.

3.2. Solid Angle with Which Proxima Centauri Is Seen from Earth

The surface radiation spreads in all directions across the hemisphere. Only a small fraction of Proxima's radiation reaches Earth. This fraction lies within the solid angle under which Proxima, with a diameter of approximately 200,000 km, is seen from Earth, located about 40×10^{12} km away. The solid angle ω_{PC} is calculated as the ratio of the visible surface area to the square of the distance:

$$\omega_{\mathrm{PC}} = \frac{100000^2 \pi}{\left(40 \times 10^{12}\right)^2} = 6.25 \times 10^{-18} \pi \text{ sr} \tag{1}$$

For comparison, the Sun as seen from Earth subtends a solid angle of 2.16×10^{-5} π steradians. The radiant energy from Proxima Centauri (hereafter Proxima) reaching Earth under such an extremely small angle is imperceptible, and consideration of this star is primarily of cognitive significance, especially in relation to its planet, Proxima b.

3.3. Effective Surface Temperature of Proxima Centauri

Astronomers employ the concept of effective temperature, which encompasses all forms of radiation, both thermal and quantum. For instance, according to source [9], the surface of this star, with a radius of 9,744,107 m, emits energy at a total rate of 5.742×10^{23} W. This implies that each square meter of its surface radiates

$G = 4.8126 \times 10^6$ W/m^2. Such radiation is interpreted as originating from a blackbody surface of the star, characterized by an effective temperature T_{ef}, as determined by the Stefan-Boltzmann law:

$$G = \sigma T_{\text{ef}}^4 \tag{2}$$

where: $\sigma = 5.6693 \times 10^{-8}$ W/(m^2·K^4) is the Boltzmann constant for black radiation, ($\varepsilon = 1$).

From Equation (2), the effective temperature of Proxima is estimated to be approximately $T_{ef} = 3050$ K, which is typical for red dwarves. The concept of effective temperature is based on the amount of energy emitted by radiation. However, it means that many components of the actual spectrum exceed the corresponding values for blackbody radiation at 3050 K. Using effective temperature to determine energy has the drawback that such a temperature does not reveal the actual energy level when considering, for example, heat exchange.

3.4. The Concept of Temperature

In contrast to the notion of effective temperature, we use here the classical concept of temperature understood as the parameter determining the direction of heat flow. Such temperature is associated with heat-exchange processes and refers to the temperature at which specific physical or chemical transformations occur, such as melting, combustion, or thermally activated reactions.

A compelling example of the significance of this definition appears when analyzing radiation from distant stars. Although such radiation is strongly diluted due to the vast distances, it can still be optically concentrated. Entropy-based considerations show that the theoretical maximum temperature to which this diluted radiation can be concentrated is exactly equal to the temperature of the radiation source as understood here.

The determination of radiation temperature—discussed later using the example of Proxima's radiation—is based on analyzing the spectral components of the star's emission.

3.5. Discussion of the Radiation Spectrum of Proxima Centauri

3.5.1. Interpretative Recalculation of the Measured Data

For the analysis of Proxima, spectral data [15] were used to determine the radiation intensity of this star as perceived at a distance of R_{AU} = 149,597,870.700 km from its surface. The dataset contains 36,313 wavelength values ranging from 120 nm to 30 μm, with monochromatic radiation intensity expressed in W/(m^2·m).

It is assumed that the radiation under consideration is nonpolarized, meaning that the principal (*i.e.*, smallest and largest) values of the monochromatic radiation intensity component are equal, see Section 7 [12]. Each of these two components represents the normal monochromatic radiation intensity i_λ in W/(m^2·m·sr), which can be calculated using a formula derived from Planck's hypothesis. Therefore, the data [15], originally given in W/(m^2·nm), were here converted to W/(m^2·m·sr).

The radius of Proxima is R_{PC} = 107,276.94 km. For concentric spheres with radii

R_{AU} and R_{PC}, the ratio of their surface areas is R_{AU}^2 / R_{PC}^2, which proportionally defines the ratio of radiation intensities at these surfaces. Directionality is accounted for by dividing by π, and further division by 2 yields the value of the unpolarized radiation component. Taking all of this into account, the required intensity i_λ is obtained from the following formula:

$$i_\lambda = i_T \frac{R_{AU}^2}{R_{PC}^2} \frac{1}{2\pi} \quad (3)$$

where i_T denotes the intensity value taken from the measured spectral table [15]. For further analysis, the recalculated data were obtained for 36,313 values of i_λ as a function of wavelength λ.

3.5.2. Selection of a Representative Wavelength Range

The recalculated values of i_λ are first used in the discussion of temperature. According to Planck's hypothesis, any place emitting a given intensity at a specific wavelength cannot have a temperature lower than a certain minimum value, as determined by Planck's formula [16]:

$$i_\lambda = \frac{c_1}{\lambda^5 \left(e^{\frac{c_2}{\lambda T}} - 1 \right)} \quad (4)$$

where:

i_λ—intensity of monochromatic black radiation, W/(m^2·m·sr),

$c_1 = hc_0^2 = 5.95416 \times 10^{-17}$ W·m^2 and $c_2 = hc_0/k = 1.4388 \times 10^{-2}$ K·m, are the first and the second, respectively, Planck's constants,

T—absolute temperature of black radiation, K,

λ—wavelength, m,

h—Planck's constant, $h = 6.625 \times 10^{-34}$ J·s,

k—Boltzmann constant, $k = 1.3805 \times 10^{-23}$ J/K,

c_0—speed of propagation of radiation in vacuum, $c_0 = 2.9979 \times 10^8$ m/s.

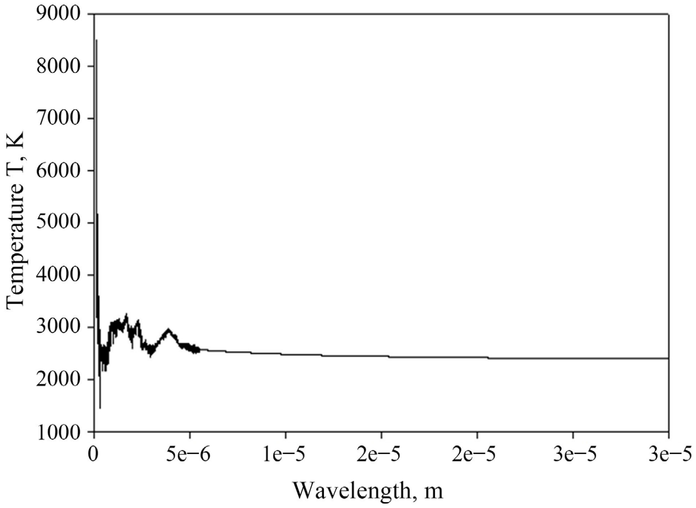

Figure 2. Calculated temperatures for full range of wavelength from 120 nm to 30 μm.

For the measured radiation spectrum of Proxima (36,313 data points) in the wavelength range from 120 nm to 30 μm [15], **Figure 2** presents the temperature values calculated using Equation (4). Relatively high temperatures occur only at short wavelengths (from 120 nm to 281 nm). **Figure 3** shows the location of the maximum temperature of 8490.6 K, (row 921, $\lambda = 121.56$ nm). **Table 1** displays a fragment of the data surrounding row 921.

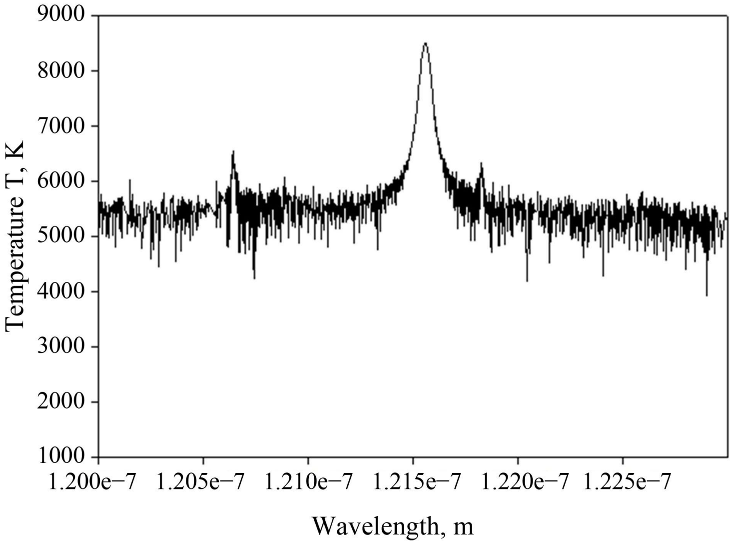

Figure 3. Calculated temperatures in the wavelength range of the highest temperature.

Table 1. Fragment of the calculation printout containing the occurrence of the maximum temperature (in row 921).

Row	λ, m	i_T, W/(m^2·μm)	i_λ, W/(m^2·m·sr)	T, K
920	1.2156e−7	6.3786	1.9741e+12	8488.88434
921	**1.2156e−7**	**6.3976**	**1.9800e+12**	**8490.6359**
922	1.2156e−7	6.3824	1.9753e+12	8489.1360

The data points, converted from irradiance in W/(m^2·m) to spectral intensity in W/(m^2·m·sr), are also shown (**Figure 4**) on the plot of Proxima's spectrum, which spans the full range of wavelengths λ, with a schematic scale, and is based on a dataset of 36,314 entries.

Since we will be working with Proxima's spectrum, it's useful to outline some basic spectral characteristics of red dwarfs. In general, stars share a similar composition, they are immense spheres of plasma composed primarily of ionized hydrogen and helium. Astronomers refer to all other elements present in stars as "metals". The metallicity of a star depends on its age, and in the case of Proxima, metals constitute only about 0.04 to 1 percent of its composition.

Stars are classified by their spectra, which vary from hottest to coolest, not due to differences in chemical composition, but because of differences in temperature. This temperature-dependent variation leads astronomers to categorize stars into spectral classes. Red dwarfs fall into the "M" spectral class.

Broadly speaking, the first notable feature of a red dwarf's spectrum is the strong presence of the Lyα (Lyman-alpha) emission line in the ultraviolet region [17]. This line arises because, at the relatively low temperatures of red dwarfs, nearly all hydrogen atoms remain in their ground (unexcited) state. These atoms preferentially absorb photons capable of exciting electrons from the first energy level to the second. When these excited atoms return to their ground state, they emit energetic Lyα photons.

The second defining feature of red dwarf spectrum is the prominent absorption bands of titanium oxide (TiO) in the red portion of the optical spectrum. At cooler temperatures, TiO molecules remain intact and do not dissociate into ions. These molecules absorb photons across a wide range of wavelengths, and when they reemit radiation, they produce numerous closely spaced spectral lines that blend to form broad absorption bands.

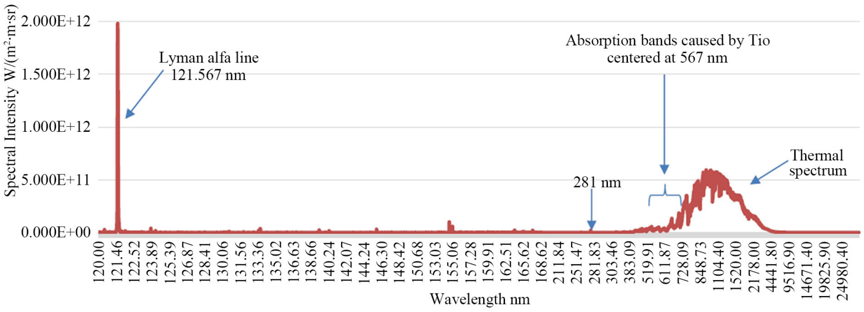

Figure 4. Spectral intensity as function of wavelength [6], recalculated to the intensity in W/(m^2·m·sr).

We will refer to these two spectral characteristics of M-class stars in our subsequent analysis. As shown in **Figure 3** and **Figure 4**, the measured full spectrum (36,313 data points) includes a range of short wavelengths (from 120 nm to 281 nm) with high intensity, corresponding to a high temperature exceeding 8000 K, as well as a range of wavelengths from 281 nm to 30 μm, for which the intensity corresponds to a temperature slightly above 3000 K.

Within the short-wavelength range, the characteristic Lyman-alpha (Lyα) line is visible. This line does not appear uniformly across every square meter of Proxima's surface [18]; rather, it is concentrated in active regions of the chromosphere and corona. It varies over time, depending on flares and the activity cycle [19]. Additionally, it is modulated by absorption in the star's surrounding environment [20]. It is likely that only a few to several percent of the surface may emit Lyα radiation at any given moment [17]. Therefore, the Lyα line does not affect the actual, perceived temperature of the star's surface (*i.e.*, the photosphere). Instead, it significantly influences how we perceive the star's activity from afar, especially in the ultraviolet range. Based on Lyα emission, one might overestimate the temperature, particularly if the full spectrum is unavailable. In the case of Proxima, which has a planet in the habitable zone (Proxima b), the variable Lyα emission affects the planet's atmosphere but does not alter the average temperature of the photosphere [17].

The following interpretation of the measured spectrum can be proposed: the surface of Proxima exhibits a non-isotropic spectrum. There is a small portion of the surface, potentially negligible, characterized by phenomena that manifest as high-intensity radiation in the short-wavelength range. The remaining, fundamentally significant portion displays a spectrum with intensities corresponding to wavelengths from 281 nm to 30 μm. Although the spectral measurement provides intensities per square meter, this representative unit area reflects the intensities from all observed square meters of Proxima's surface included in the measurement. Therefore, in further analysis, we exclude the spectrum for the wavelength range from 120 nm to 281 nm (points 1 to 23,517). We assume that the spectrum for the remaining 12,796 points (from point 23,518 to 36,313) represents a surface with uniform temperature across all its locations.

Figure 5 presents temperatures calculated using Equation (4), corresponding to the measured intensity values at each wavelength within the considered range of 281 nm to 30 μm. Within this range, adopted for further analysis, the maximum temperature is 3255.4 K (row 30639, λ = 1679 μm).

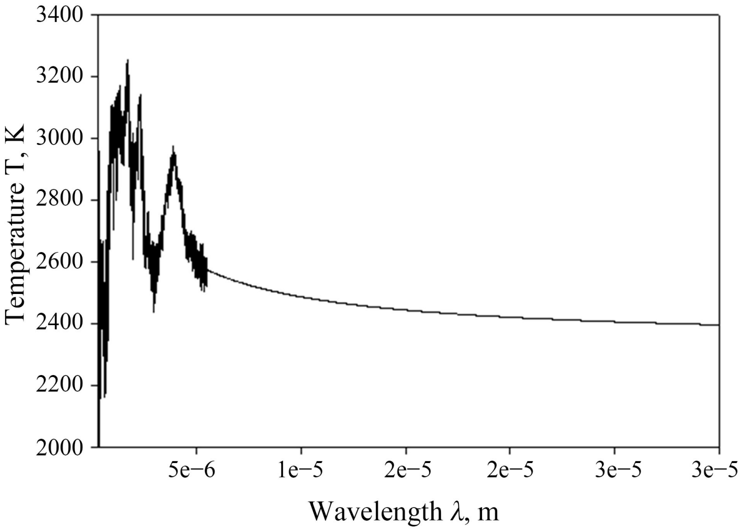

Figure 5. Temperatures calculated for intensities in the long-wavelength range (281 nm - 30 μm).

Thus, in accordance with the adopted methodology, a wavelength range was selected for further analysis to represent the characteristic spectrum of Proxima.

4. Proxima Centauri

The actual spectrum of Proxima differs from that of a blackbody due to the irregularity of its graph, in which many spectral components exceed the corresponding components of blackbody radiation at the effective temperature T_{ef}. As mentioned before, this temperature arises from a certain interpretation of the amount of energy. However, this raises the question: what really is the temperature of the surface of Proxima?

The irregularity of the spectral graph indicates that the considered surface of Proxima is not a blackbody. Nevertheless, there exists a specific value of certain temperature T_t such that no measured intensity of Proxima, at any given wavelength, exceeds the intensity of blackbody radiation at temperature T_t. In other words, all intensities of Proxima lie beneath the dome of the blackbody curve at temperature T_t. Naturally, any temperature higher than T_t also ensures that no measured spectral component of Proxima surpasses the corresponding blackbody intensity at that temperature. Therefore, this temperature T_t is simply the minimal value for which the above non-exceedance condition is satisfied. The temperature T_t, at which the actual spectral graph touches the blackbody curve at only one point, may also be referred to as the minimal temperature $T_{\min,PC}$ of Proxima's surface.

The spectral distribution for Proxima Centauri, comprising 12,796 data points, is shown in **Figure 6**. For comparison, **Figure 6** also presents the blackbody spectrum for the effective temperature $T_{ef} = 3050$ K (dashed line), as well as the blackbody spectrum whose components were calculated using Equation (4) for the surface temperature of Proxima $T_t = 3255$ K.

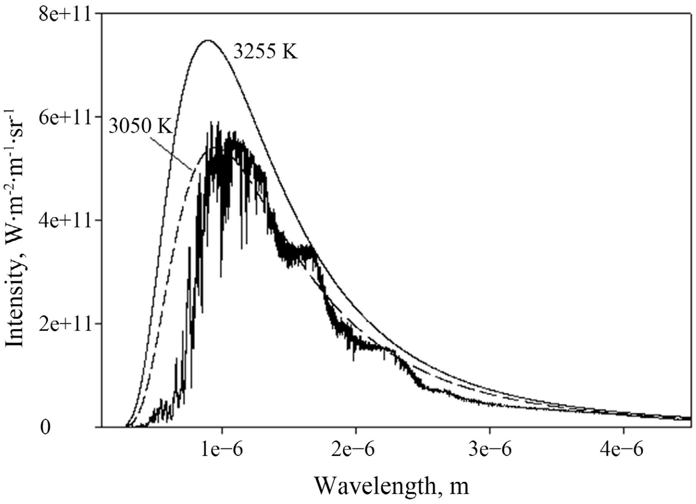

Figure 6. The radiation spectrum of the star Proxima Centauri compared with the blackbody spectrum at the effective temperature $T_{ef} = 3050$ K (dashed line) and with the blackbody intensity spectrum corresponding to the temperature $T_t = 3255$ K (solid line).

Thus, according to the proposed interpretation [11], the temperature defined here is equal to the minimal possible surface temperature of Proxima Centauri, $T_t = T_{\min,PC}$. The star's spectrum touches the blackbody spectrum at temperature of ~3255 K at only one point (**Figure 6**, row 30,639, $\lambda = 1.679$ μm).

5. Ambiguity of the Temperature of the Star's Surface and Its Emissivity

As previously noted, any temperature exceeding $T_{\min,PC}$ meets the criterion that no observed component of Proxima's spectrum surpasses the corresponding radiation intensity at $T_{\text{min,PC}}$. For determined amount of stellar radiation received, this implies that the elevated temperatures are accompanied by a simultaneous reduction in surface emissivity, the higher the temperature, the lower the emissivity. This observation leads to the following condition of ambiguity:

$$G = \varepsilon_{\max}\sigma T_{\text{min,PC}}^{4} = \varepsilon\sigma T^{4} \quad (\text{for } \; T > T_{\text{min,PC}} \quad \text{where } \; \varepsilon < \varepsilon_{\max}) \tag{5}$$

where ε is the emissivity of Proxima's surface, indicating the degree of its blackness and $\sigma = 5.6693 \times 10^{-8}$ W ($\text{m}^2 \cdot \text{K}^4$) is the Stefan-Boltzmann constant. Condition (5) means that as the value of surface temperature T of the star is uncertain, $T > T_{\text{min}}$, uncertain is also the emissivity of the star surface.

However, if we assume the star surface temperature, for instance, $T_{\text{min, PC}} = 3255$ K, then using the values $G = 4.8126 \times 10^{6}$ W/m^2, (from Section 3.3) in Equation (5) yields a surface emissivity for Proxima of $\varepsilon_{\max} = 0.757$. However, a more justified value of energetic emissivity for this star is determined in Section 6.3.

6. Planet Proxima b

This planet is relatively close to its star, so the star's radiation is already quite intense on the planet's surface. Therefore, it is worth discussing the amount of radiant energy reaching planet from Proxima, as well as the exergy of that radiation. Thus, following a brief description of the planet, the energy and exergy of the stellar radiation reaching it are examined.

6.1. About Planet Proxima b

Proxima b is an Earth-like exoplanet orbiting the closest star to us, Proxima. It was discovered only in 2016 by a team led by Guillem Anglada-Escudé from ESO [9]. Located at approximately 4.24 light-years from Earth, it is the closest known planet outside the Solar System. As already mentioned, the planet is rocky and similar in size to Earth (mass ~1.27 Earth mass). It has an orbit very close to its star, about 7.25 million kilometers. It lies within the so-called habitable zone [5], meaning the distance from the star where liquid water could theoretically exist. The surface temperature is estimated to be around 234 K (about −39˚C). Although Proxima is cooler and less luminous than the Sun, its activity (e.g., flares) may affect the planet's atmosphere [18]. Its significance stems from the fact that Proxima b is one of the most promising targets in the search for extraterrestrial life. If Proxima b has an atmosphere, it may be very different from Earth's [5] and is suspected to consist mainly of hydrogen and helium, rather than oxygen and nitrogen [2].

For Proxima b to be habitable, it needs a sufficient amount of water and atmospheric gases able to maintain a surface pressure and possibly a greenhouse effect, typically, with carbon dioxide (−39˚C is actually estimated at the top of its atmosphere). If its eccentricity is higher than ~0.06, it could be captured into spin-orbit resonances [5]. The climate on tidally locked and synchronous planet can be very different from the asynchronous case.

The proximity of Proxima b makes it potentially the first planet outside the Solar System to be thoroughly investigated within a decade or so by direct imaging [4]. Scientist's research on Proxima b is intensifying, therefore exergy-related issues could be considered for this planet, such as stellar radiation exergy and exergy emissivity.

6.2. Solid Angle within Which Proxima b Sees Proxima Centauri

Proxima has a diameter of approximately 200,000 km. Proxima b has an approximate diameter of 13,100 km, and its estimated distance from Proxima is 7.25 × 10^6 km [9]. The solid angle ω_{Pb} under which Proxima is seen from the surface of Proxima b, that is, the ratio of surface area to the square of the distance, is given by:

$$\omega_{\text{Pb}} = \frac{\pi \times 100000^2}{\left(7.25 \times 10^6\right)^2} = 1.9 \times 10^{-4} \pi \text{ sr} \tag{6}$$

This angle is approximately 9 times larger than the angle (2.16 × 10^{-5} π·sr) under which the Sun is seen from Earth.

6.3. Radiation Energy from Proxima Reaching Proxima b

We assume that the radiation from Proxima reaching the surface of Proxima b is unpolarized and propagates uniformly in all directions. In this case, the monochromatic radiation intensity depends only on the wavelength λ, and the radiation energy E in watts per square meter (W/m^2) reaching the planet is given by [12], Chapter 7:

$$E = 2\omega_{\text{Pb}} \int i_\lambda \mathrm{d}\lambda \tag{7}$$

where i_λ, W/(m^2·m·sr), is the measured monochromatic directional intensity. The integral in Equation (7) can be determined numerically based on the measurement results:

$$\int i_\lambda \mathrm{d}\lambda = \sum_{n=23518}^{n=36313} (\Delta\lambda)_n (i_\lambda)_n \tag{8}$$

where n is the successive number of the row in the measurement results table and

$$(\Delta\lambda)_n = \frac{\lambda_{n+1} - \lambda_{n-1}}{2} \tag{9}$$

The integral value was determined as 6.49776 × 10^5 W/(m^2·sr). It is worth noting that the numerically determined definite integral over the entire wavelength range (including all 36,313 points) has a value of 6.499252621 × 10^5 W/(m^2·sr), which is only 0.0223% greater. Excluding the intensity values for the short-wavelength range has practically no significance from an energetic standpoint. Therefore (7):

$$E = 2 \times 1.9 \times 10^{-4} \pi \times 6.49776 \times 10^5 = 775.7 \frac{\text{W}}{\text{m}^2} \tag{10}$$

Equation (2), which is used in the literature to calculate the effective temperature T_{ef}, can now, based on the results obtained here, be applied in the following way: $2\times\pi\times 6.4977\times 10^5 = \sigma T_{\text{ef}}^4$, from which it follows that $T_{\text{ef}} = 2913.09\ \text{K}$. Using expression (5), one obtains the emissivity corresponding to the temperature of 3255 K:

$$\varepsilon_{\text{e}} = \left(\frac{2913.09}{3255}\right)^4 = 0.6415 \tag{11}$$

The obtained value $\varepsilon_{\text{e}} = 0.6415$ is smaller than the value 0.757 determined in Section 5 for $G = 4.8126 \times 10^6\ \text{W/m}^2$.

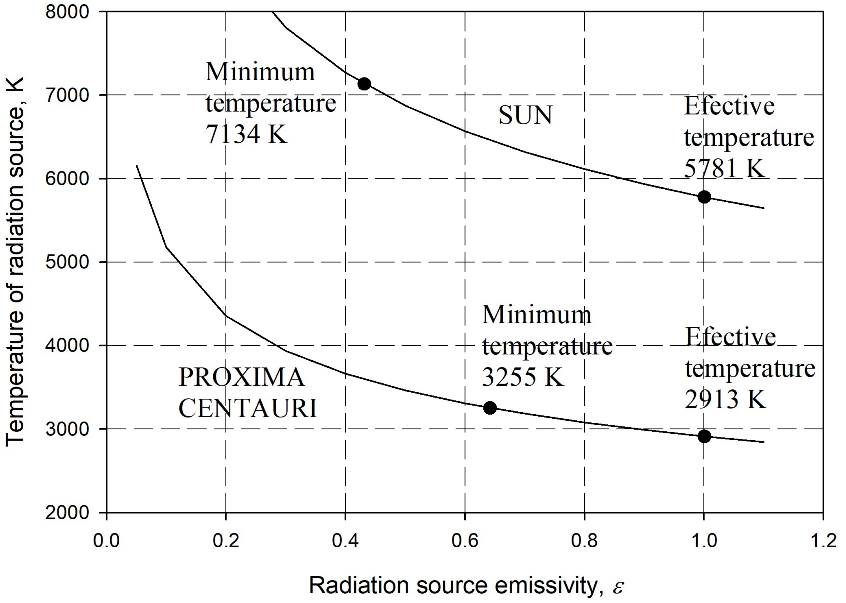

Figure 7. Curves of possible values of the radiation temperature of Proxima Centauri and the Sun.

According to relation (5), for a given amount of radiation energy arriving from some source, the product of the fourth power of the radiation temperature and the emissivity of the radiating object remains constant. This hyperbolic relationship can be illustrated with the plot shown in **Figure 7**, where, for comparison, the hyperbola for Proxima's radiation is shown alongside the corresponding hyperbola for solar radiation. The effective temperature of a radiating source, given by Equation (2), follows from the amount of radiation energy reaching a planet. It is calculated on the basis of the Stefan-Boltzmann law, assuming a blackbody source. The values of this effective radiation temperature lie on the appropriate curves for Proxima and for the Sun (**Figure 7**). Values on the curve to the right of the effective temperature are not physically realistic ($\varepsilon > 1$).

Figure 7 also shows the position of the minimum radiation temperature determined from the interpretation of Planck's law (Section 3.5.2). The actual radiation temperature of the star lies somewhere on the hyperbola, but to the left of this minimum value. (A temperature between the effective and the minimum value is not possible, because it would contradict Planck's law.) The conclusion is that the surface of a star, taken as some conventional boundary of its volume, may have a very high temperature as a consequence of the extremely hot interior. However, according to relation (5), the effect of such a high temperature would be mitigated by the fact that the higher the temperature, the lower the emissivity, meaning a reduced ability to radiate energy outward.

In more intuitive terms, it is as if some mechanisms were at work that increase the efficiency of "self-insulation" as the temperature rises. For example, this is fortunate for life on Earth, which is therefore not threatened by catastrophic over-irradiation from the Sun. The issue raised here may well deserve a separate, more extensive treatment.

6.4. Outline of the Procedure for Determining the Radiation Temperature of a Star

One may formulate a general procedure for determining the radiation temperature of a star as experienced by a planet, provided that the stellar radiation spectrum is known. The first step is to calculate the radiant energy reaching 1 m^2 of the planet's surface. The second step is to determine the effective radiation temperature using Equation (2). The third step is to determine the minimum possible radiation temperature based on Planck's law, using Equation (4). The fourth step is to establish the hyperbolic curve (**Figure 7**), from which the actual radiation temperature is obtained. This temperature lies on that curve and is not lower than the minimum temperature derived from Planck's law.

6.5. Exergy of Proxima Centauri's Radiation at the Surface of Proxima b

Generally, exergy is used to estimate the practical value of energy [12], Chapter 4. The exergy B in W/m^2 of nonpolarized and uniform radiation is given in [12], Chapter 7:

$$B = \omega_{\mathrm{PCb}}\left(2\int i_\lambda \mathrm{d}\lambda - 2T_{\mathrm{P,0}}\int L_\lambda d\lambda + \frac{\sigma T_{\mathrm{P,0}}^4}{3\pi}\right) \tag{12}$$

where $T_{\mathrm{P,0}}$ = 234 K is the environment temperature prevailing at the surface of Proxima b, and L_λ denotes the entropy of monochromatic intensity of radiation, expressed in W/(m^{-2}·m·K·sr), calculated using the formula derived by Planck [16]:

$$L_\lambda = \frac{c_0 k}{\lambda^4}\left[(1+Y)\ln(1+Y) - Y\ln Y\right] \tag{13}$$

where:

$$Y \equiv \frac{\lambda^5 i_\lambda}{c_0^2 h} \tag{14}$$

and $c_0 = 2.9979 \times 10^8$ m/s is the speed of radiation propagation in vacuum, $h = 6.625 \times 10^{-34}$ J·s, is Planck's constant, and $k = 1.3805 \times 10^{-23}$ J/K is the Boltzmann constant.

The entropy integral in Formula (12) can be calculated numerically using the following expression:

$$\int L_\lambda \mathrm{d}\lambda = \sum_{n=23518}^{n=36313} (\Delta\lambda)_n (L_\lambda)_n \tag{15}$$

in which $(\Delta\lambda)_n$ is determined using Formula (9). From Formula (15), we obtain:

$$\int L_\lambda \mathrm{d}\lambda = 294.939\ \mathrm{W}/\left(\mathrm{m}^2 \cdot \mathrm{m} \cdot \mathrm{sr} \cdot \mathrm{K}\right) \tag{16}$$

Substituting (16) to Formula (12):

$$\begin{aligned} B &= 1.9\times10^{-4}\pi\left(2\times6.49776\times10^5 - 2\times234\times294.939 + \frac{5.6693\times10^{-8}\times234^4}{3\pi}\right) \\ &= 693.3\frac{\mathrm{W}}{\mathrm{m}^2} \end{aligned} \tag{17}$$

The exergy-to-energy ratio is given by $E/B = 693.3/775.7 = 0.8938$. This value can be compared to the theoretical exergy-to-energy radiation ratio ψ, which is analogous to Carnot efficiency. It represents the maximum exergetic value of energy radiated from any black surface. The ratio ψ is calculated using the formula provided in [12], Chapter 6:

$$\psi = 1 + \frac{1}{3}\left(\frac{T_{\mathrm{P},0}}{T_\mathrm{t}}\right)^4 - \frac{4}{3}\frac{T_{\mathrm{P},0}}{T_\mathrm{t}} \tag{18}$$

From (18), one obtains $\psi = 0.9042$, which is larger than $E/B = 0.8938$.

The exergetic emissivity ε_b of the Proxima surface, as experienced at the surface of Proxima b, is defined as the ratio of the exergy B received at the surface of Proxima b to the exergy B_b of a black surface at temperature T_t [12], Chapter 6:

$$B_\mathrm{b} = \frac{\sigma}{3}\left(3T_\mathrm{t}^4 + T_{\mathrm{P},0}^4 - 4T_{\mathrm{P},0}T_\mathrm{t}^3\right)\omega_{\mathrm{PCb}} \tag{19}$$

From Formula (19), $B_\mathrm{b} = 3434.6\ \mathrm{W/m^2}$, therefore $\varepsilon_\mathrm{b} = 693.3/3434.6 = 0.2019$.

7. Conclusions

This study presents primarily a novel application of radiation exergy analysis to a stellar system beyond Earth, focusing specifically on Proxima Centauri and its exoplanet Proxima b.

The investigated phenomena are complex, and therefore, in this first approach, aimed at enabling the calculation of practical engineering quantities, many simplifying assumptions were required. These include, for example, neglecting stellar variability, corona phenomenon and planetary eccentricity, as well as introducing idealized models, such as replacing the radiation of a plasma body with that of a solid surface.

Instead of adopting the commonly cited effective temperature of Proxima Centauri (3050 K), this work determines the temperature of its radiating surface as a more physically meaningful parameter for evaluating heat exchange and energy quality. The temperature of Proxima Centauri was found to be at least

3255 K, representing the minimum temperature at which the blackbody radiation envelope fully encompasses the measured stellar spectrum. The ambiguity associated with this value is discussed, and further dedicated analysis is recommended.

Furthermore, the radiation energy and exergy reaching the surface of Proxima b were calculated, yielding 775.7 W/m^2 and 693.3 W/m^2, respectively. These values reflect the quantity and usability of the incoming radiation relative to the planet's surface conditions. The corresponding energetic and exergetic emissivity of Proxima Centauri, as experienced on Proxima b, were determined to be 0.6415 and 0.2019.

The results obtained in this work may find relevance in various future endeavors. For example, the proposed radiating-surface temperature of 3255 K for Proxima Centauri provides a more appropriate theoretical upper limit for the concentration of diluted stellar radiation [21], which may be of practical importance for future energy conversion technologies. An increase in the exergy of Proxima Centauri's radiation at the surface of Proxima b may be achieved through spectral splitting of the incident radiation [22]. The potential for enhancing radiation exergy through spectral splitting, previously proposed for solar applications, could be explored under the unique conditions prevailing on Proxima b. Given these conditions, such splitting may be more efficient than analogous processes applied to solar radiation on Earth.

The resulting value of 3255 K represents the minimal possible surface temperature of Proxima Centauri consistent with the non-exceedance condition relative to blackbody radiation. Any higher temperature remains admissible, provided it is accompanied by a proportionally lower emissivity, which introduces an inherent ambiguity in the temperature-emissivity pair.

The methodology developed here, previously applied to the Sun and now extended to Proxima Centauri, is general and can be used for other stars for which spectral data are available.

The proximity of Proxima b to its host star makes it a compelling candidate for further thermodynamic and exobiological investigations. The methodology presented here, combining spectral analysis, thermodynamic modeling, and exergy evaluation, may serve as a foundation and a source of inspiration for future studies of other exoplanetary systems. In light of rapidly advancing AI, the information contained here, which may seem of limited importance today, could one day prove to be highly valuable.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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