Complete and Commented Translation of Guillaume's 1896 Paper on the Temperature of Space

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Abstract

Charles Édouard Guillaume (1861-1928) was a Swiss physicist who received the 1920 Nobel Prize in physics for his precision measurements and discovery of anomalies in nickel steel alloys. In this work we present a complete and commented translation of his remarkable article of 1896 on the temperature of interstellar space. The importance of this work is that it is the oldest estimate known to us of the temperature acquired by a black body which is in interstellar space far from other stars. This temperature was presumed to be due to an equilibrium state in which the radiation received by this body from the stars around it would be equal to the radiation emitted by the body. He arrived at a temperature of 5.6 K, regarding this figure as an upper limit on the effect he was seeking to estimate. In 1926 Arthur Eddington (1882-1944) arrived at a temperature of 3.18 K utilizing essentially the same procedure but with better data.

I. INTRODUCTION

Charles Édouard Guillaume was born on February 15, 1861, in Fleurier, Switzerland, and died on May 13, 1938, in Sèvres, France. He was the son of a Swiss horologist. He obtained his PhD in physics at ETH Zurich in 1883, and served as the head of the International Bureau of Weights and Measures in Sèvres from 1915 to 1936. He was a Grand Officer of the Legion of Honor and President of the French Physical Society. In 1896 he discovered two nickel-steel alloys named invar and elinvar. The first has a near-zero coefficient of thermal expansion while the second has a near-zero thermal coefficient of the modulus of elasticity. He was awarded the 1920 Nobel Prize in physics with the following mention:[1]

> "in recognition of the service he has rendered to precision measurements in Physics by his discovery of anomalies in nickel alloys."

In 1896 Guillaume published a paper in two parts on the temperature of space (part 1 on pages 210-211 and part 2 on page 234).[2] The second part has already been translated into Portuguese.[3] In this work we present a complete and commented English translation of the whole paper.

The work which is translated here is the oldest estimation known to us of the temperature acquired by a black body in interstellar space far from other stars. This temperature was assumed to be due to an equilibrium state in which the radiation received by this body from the surrounding distant stars is equal to the radiation emitted by this body. To arrive at the equilibrium temperature he utilized the 1879 law due to Josef Stefan (1835-1893). It is a physical power law stating that the total energy radiated per unit surface area from a black body across all wavelengths per unit time, that is, the bolometric radiated power P per unit area, is directly proportional to the fourth power of its temperature T:

$$P = \sigma T^4 \ . \tag{1}$$

Here the constant of proportionality $\sigma = 5.67 \times 10^{-8}\ Wm^{-2}K^{-4}$.

A derivation of the law from theoretical considerations was presented by Ludwig Boltzmann (1844-1906) in 1884. Stefan had been one of his teachers at the University of Vienna. The constant σ is now called the Stefan-Boltzmann constant.

In 1926 Arthur S. Eddington (1882-1944) published the book *The Internal Constitution of the Stars*. The last Chapter of this work is titled "Diffuse Matter in Space" and begins with a discussion of the temperature of space, a subject which he also discussed in his Bakerian Lecture of the same year.[4,5]

The beginning of the Chapter runs as follows:

Chapter XIII

Diffuse Matter in Space

The Temperature of Space.

256. The total light received by us from the stars is estimated to be equivalent to about 1000 stars of the first magnitude.[6,7] Allowing an average correction to reduce visual to bolometric magnitude for stars of types other than F and G, the heat received from the stars may be taken to correspond to 2000 stars of apparent bolometric magnitude 1.0. We shall first calculate the energy-density of this radiation.

A star of bolometric magnitude 1.0 radiates 36.3 times as much energy as the Sun or 1.37×10^{35} ergs per sec. This gives 1.15×10^{-5} ergs per sq. cm. per sec. over a sphere of 10 parsecs (3.08×10^{19} cm.) radius. The corresponding energy-density is obtained by dividing by the velocity of propagation and amounts to 3.83×10^{-16} ergs per cu. cm. At 10 parsecs distance the apparent magnitude is equal to the absolute magnitude; hence the energy-density 3.83×10^{-16} corresponds to apparent bolometric magnitude 1.0.

Accordingly the total radiation of the stars has an energy-density

$$2000 \times 3.83 \times 10^{-16} = 7.67 \times 10^{-13} \text{ ergs/cm}^3 \ .$$

By the formula $E = aT^4$ the effective temperature corresponding to this density is

$$3^\circ.18 \text{ absolute.}$$

In a region of space not in the neighbourhood of any star this constitutes the whole field of radiation, and a black body, e.g. a black bulb thermometer, will there take up a temperature of 3°.18 so that its emission may balance the radiation falling on it and absorbed by it. This is sometimes called the 'temperature of interstellar space.'

Although Eddington did not quote any sources in this Section of the book, he may be referring to Guillaume's work of 1896. Guillaume was a well-known scientist who had received the Nobel prize in 1920, just six years before. Moreover, in the title of this Section Eddington utilized the same expression as the title of Guillaume's paper, namely, "the temperature of space". Another indication in this direction is that Eddington was not claiming that he was the author of this estimate. Moreover, he wrote that this temperature is sometimes called [by whom?] the temperature of interstellar space.

Other scientists arrived at temperatures close to 3 K in the following years: Erich Rudolf Alexander Regener (1881-1955) in 1933 (2.8 K); Walther Hermann Nernst (18964-1941) in 1937-1938 (2.8 K); Gerhard Herzberg (1904-1999) in 1941 (2.3 K); Erwin Finlay-Freundlich (1885-1964) and Max Born (1882-1970) in 1953-1954 ($1.9\ K \leq T \leq 6.0\ K$); George Anthony Gamow (1904-1968), Ralph Asher Alpher (1921-2007) and Robert Herman (1914-1997) in 1948-1961 ($5\ K \leq T \leq 50\ K$) etc.[8–22] These works estimated the temperature of a black body in equilibrium with the surrounding radiation via the Stefan-Boltzmann law. It is important to emphasize that these scientists tackled the problem by placing themselves in two different scientific contexts. Guillaume, Eddington, Regener, Nernst, Herzberg, Finlay-Freundlich and Max Born considered a universe in dynamical equilibrium without expansion, without a big bang and without continuous creation of matter. On the other hand, Gamow and his collaborators Alpher and Hermann, worked within the context of the big bang theory with an expanding and cooling universe, and their interpretation of the meaning of the "temperature of space" was different.

As we have already discussed these works in other papers,[23–28] we present here the translation of Guillaume's paper. We have inserted all footnotes in the translation and also the text between square brackets, [ ].

ACKNOWLEDGMENTS:

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II. TRANSLATION

The Temperature of Space[29]

Ch.-Ed. Guillaume

Various opinions have been circulating as to the temperature of interplanetary or interstellar space. Some astronomers, basing themselves on the idea that space, being empty of matter, cannot have a temperature in the strict sense, admit that space in its entirety behaves as if it were at absolute zero, i.e., 275 degrees C below the temperature at which ice melts.[30] Others, meanwhile, think that the temperature of space is what we find in the highest regions of the atmosphere, where there is an imperceptible transition from matter to void. This leads them to assign space a temperature lying between 30 and 100 degrees [Celsius] below zero.

In reality, this difference of opinion rests on a misunderstanding that can very easily be rectified. It is difficult to imagine that an empty space could have a temperature, and we may feel that the definition of this property of space is completely arbitrary.

In my view the problem is not so hopeless. It is true that, in general, the temperature of radiation is a vague notion to which we attribute a precise meaning by means of an artifice. However, the temperature of radiation can exist in reality, as Kirchhoff has shown.[31–38] Recently, W. Wien has given this notion a more precise form that can be applied to the present problem.[39] The idea put forward by Kirchhoff and Wien is that radiation has a temperature when it is emitted from a body which, across the entire visible and invisible spectrum, possesses the properties a black body has in the visible spectrum. By extension, we give a body of this type the name *black body*, and we will surmise that it absorbs all the radiation it receives. Moreover, as Mr. Wien has shown, we can construct a space that has this property. Any closed isothermic container that does not contain phosphorescent bodies is a black body, and the radiation contained within it is in equilibrium. The distribution of its wavelengths has a definite form, which is always the same for the same temperature.

Having stated this, we can define the temperature of space as being equal to what a perfectly black body would assume when immersed in it, since the radiation is assumed to be uniform in all directions. If this condition is not fulfilled, a poorly conducting body will heat up on the side of the stronger sources and lose heat in other directions. The temperature of the interior of the body will be a complicated function of the distribution of sources, and even its average temperature will not correspond to the temperature of space at this point. It should be further added that the body used as a test sample must be a good conductor [of heat]. For this very reason, it must be spherical in shape.

Once this definition is allowed, the problem immediately assumes a precise form, and can be solved numerically in all cases where we have sufficient data on heat sources capable of influencing the radiation at a given point. We will apply this to a few especially important cases.

First, consider a body that is completely isolated in an indefinite space which contains no other bodies and no sources of heat. The energy will dissipate as radiation, and the body's temperature will fall to absolute zero.

Now let us place our test body at a point in the Earth's orbit, far from our planet. The only radiation that we will need to consider is radiation from the Sun, since radiation from the stars is negligible in this case, as we will show in a moment.

The problem can be solved quite simply by assuming that, when in equilibrium, the body radiates as much heat into space, which is devoid of energy, as it receives from the Sun.

To give the problem a definite form, we must adopt a well-defined law for the expression of energy of radiation as a function of temperature. Stefan's law is considered the most accurate, and in fact this law expresses the effective temperature of the Sun as a function of the intensity of its radiation. The law tells us that the energy of the radiation is proportional to the fourth power of the absolute temperature of the source.

For the temperature of the Sun, we will assume a value of 7000 degrees [Celsius], which seems accurate to within 1000 degrees. The apparent surface of the Sun, seen from a point on the Earth's orbit, is about 185,000 times smaller than the entire surface of the celestial sphere. The temperature of the test body is thus given by the equation

$$7000^4 = 185,000 \times \theta^4 \ .$$

From this we deduce

$$\theta = 338 \ K = + \ 65^\circ \ C \ .$$

If the half of the test body not exposed to the Sun is in contact with an insulating body, we should write

$$7000^4 = 92,500 \times \theta^4 \ .$$

and we have:

$$\theta = 402\ K = 129^\circ\ C\ .$$

Consequently, we can say that the temperature of space in the Earth's orbit is about 65 degrees C; by contrast, a non-conducting spherical black body located on this orbit will assume an average temperature of $+129^\circ\ C$ on the side directed toward the Sun.

Using an analogous calculation, we can find the temperature at various points of the solar system, as shown in the table below:

Orbit of	Temperature
Mercury	$+\ 156^\circ\ C$
Venus	$+\ 94$
Mars	$+\ 32$
Small planets	$-\ 9$
Jupiter	$-\ 49$
Saturn	$-\ 80$
Uranus	$-\ 102$
Neptune	$-\ 132$

These temperatures should not be confused with the temperature each of the planets, left to itself, would tend to acquire due to the action of solar radiation, which we will assume to be constant. The calculation behind the result given above is based on simplified hypotheses, which hardly apply to the planets.

We have assumed the existence of an absolutely black, perfectly conducting spherical body at some point on the orbit. However, celestial bodies exhibit non-negligible reflection. Consequently they do not absorb all the Sun's heat, and their final temperatures will probably be lower than those given by this calculation. In addition, the lack of conductivity of celestial bodies produces a temperature deficit due to the fact that the law of emission varies as the fourth power of temperature. Any departure from uniformity in the temperature should thus yield an increase in radiation.

Lastly, two factors act in the opposite direction: first, celestial bodies possess an internal heat generated when they were formed. In addition, many of them have atmospheres which are more transparent for low wavelengths than for long wavelength radiation. These act like the glass in a greenhouse, where the radiation passes more easily in one direction than the other. But these two causes cannot be invoked for small planets, which have had time to cool completely, and which, according to the kinetic theory of the conservation of atmosphere, are not accompanied by a gas envelope. We can therefore assert that their temperatures are below those arrived at by the simplified calculation of which we have given the results.

The calculation we have given for temperatures at different points of space is necessarily quite approximate; however, it should be noted that the fourth power law substantially reduces the errors due to any estimates. For example, if we were off in the ratio of 1 to 100 in our estimation of heat sources, this would result in an error [in the ratio] of 1 to 3.2 in the final figure. Consequently, we may attempt to calculate the temperature of space far from any large source, even though data on the intensity of distant sources are almost entirely lacking.

Let us suppose a body is exposed only to stellar radiation, i.e., a celestial body without any fixed stars in its vicinity. Its final temperature will be essentially equal to the temperature the surface of a planet constantly facing away from the Sun would assume. For example, this is the temperature to which the far side of the Moon would tend at the end of opposition when it had not been exposed to the Sun or Earth for fourteen days.

When we try to calculate the increase of temperature produced at a point in space by radiation from stars, we come up against a major difficulty in estimating the energy they radiate. For lack of a better theory, we will first admit that the distribution of energy in stellar spectra is the same as in our Sun, and that the radiative energy is, like the Sun, in the same proportion as the light or photographic intensity of different celestial bodies.

We have available several methods for estimating the energy radiated by stars. One is to determine the radiation of a star of the first magnitude, and from this deduce the radiation of all celestial bodies, applying Gould's formula for assigning stars to different magnitudes.[40–43] But this process is still difficult to apply, as the radiative energy of the brightest stars is just at the limits of measurement of our most sensitive instruments. Moreover, Gould's formula was established for a certain number of stellar magnitudes, and in the case that concerns us, we are reduced to extrapolating, which is not without risk. Here we will adopt a simpler method, which involves deriving a direct estimate of the total photographic action of the stars and Sun. Captain Abney has recently determined the ratio of the light from the starry sky to that of the full Moon.[44,45] It turns out to be 1/44, after reductions for the obliqueness of the rays relative to the surface, and for atmospheric absorption. Doubling this for both hemispheres, and adopting 1/600000 as the ratio of the light intensity of the Moon to that of the Sun (a rough average of the measurements by Wollaston,[46] Bouguer[47] and Zöllner[48]), we find that the Sun sends us $15,200,000$ times more vibratory energy than all the stars combined. The increase in temperature of an isolated body in space subject only to the action of the stars will be equal to the quotient of the increase of temperature due to the Sun on the Earth's orbit divided by the fourth root of $15,200,000$, or about 60. Moreover, this number should be regarded as a minimum, as the measurements taken by Captain Abney in South Kensington may have been distorted by some extraneous sources of light. We conclude that the radiation of the stars alone would maintain a test particle we suppose might have been placed at different points in the sky at a temperature of $338/60 = 5.6$ absolute $= -267.4$ centigrade.

We must not conclude that the radiation of the stars raises the temperature of the celestial bodies to 5 or 6 degrees. If the celestial body in question already has a temperature that is very different from absolute zero, its loss of heat is much greater. We will find the increase of temperature due to the radiation of the stars by calculating the loss using Stefan's law. In this way, we find that for the Earth, the temperature increase due to the radiation of the stars is less than one hundred-thousandth of a degree. Furthermore, this figure should be regarded as an upper limit on the effect we seek to evaluate.

Once again, we must stress the considerable uncertainty in the numbers we have just calculated. For the time being, we can only consider this an order of magnitude. However, we feel that they are close enough to establish, in cases beyond doubt, that some planets must be uninhabitable. In any case, it appears highly unlikely that the fixed stars play any role in the thermal phenomena of the solar system.

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[1] Nobel Media. Charles Edouard Guillaume — Facts. Available at <https://www.nobelprize.org/prizes/physics/1920/guillaume/facts/>.

[2] C. E. Guillaume, "La température de l'espace," La Nature **1214**, 210–211 and 234 (1896).

[3] A. K. T. Assis and M. C. D. Neves, "Tradução comentada do artigo de Guillaume de 1896 sobre a temperatura do espaço," Caderno Brasileiro de Ensino de Física **31**, 564–570 (2014). Doi: 10.5007/2175-7941.2014v31n3p564.

[4] A. S. Eddington, *The Internal Constitution of the Stars* (Cambridge University Press, Cambridge, 1988), pp. 371–2. Reprint of 1926 edition.

[5] A. S. Eddington, "Diffuse matter in interstellar space," Proceedings of the Royal Society A **111**, 424–456 (1926). Doi: 10.1098/rspa.1926.0076.

[6] In his book Eddington did not mention the name of the person who made this estimation. But in his Bakerian Lecture of 1926 he quoted Chapman's paper of 1914.

[7] S. Chapman, "On the total light of the stars," Monthly Notices of the Royal Astronomical Society **74**, 446–451 (1914). Doi: 10.1093/mnras/74.5.446.

[8] E. Regener, "Der Energiestrom der Ultrastrahlung," Zeitschrift für Physik **80**, 666–669 (1933).

[9] E. Regener, "The energy flux of cosmic rays," Apeiron **2**, 85–86 (1995). English translation by G. Moesle.

[10] W. Nernst, "Weitere Prüfung der Annahne eines stationären Zustandes im Weltall," Zeitschrift für Physik **106**, 633–661 (1937).

[11] W. Nernst, "Die Strahlungstemperatur des Universums," Annalen der Physik **32**, 44–48 (1938).

[12] W. Nernst, "Further investigation of the stationary universe hypothesis," Apeiron **2**, 58–71 (1995). English translation by P. Huber *et al.*

[13] W. Nernst, "The radiation temperature of the universe," Apeiron **2**, 86–87 (1995). English translation by G. Moesle.

[14] G. Herzberg, *Molecular Spectra and Molecular Structure*, volume 1: Spectra of Diatomic Molecules (D. Van Nostrand, New York, 1941).

[15] E. Finlay-Freundlich, "Über die Rotverschiebung der Spektrallinien," Nachrichten der Akade-

mie der Wissenschaften in Göttingen Mathematisch-Physikalische Klasse **7**, 95–102 (1953).

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[17] E. Finlay-Freundlich, "Red shifts in the spectra of celestial bodies," Philosophical Magazine **45**, 303–319 (1954).

[18] M. Born, "Theoretische Bemerkungen zu Freundlich's Formel für die stellare Rotverschiebung," Nachrichten der Akademie der Wissenschaften in Göttingen Mathematisch-Physikalische Klasse **7**, 102–108 (1953).

[19] M. Born, "On the interpretation of Freundlich's red-shift formula," Proceedings of the Physical Society A **67**, 193–194 (1954).

[20] R. A. Alpher and R. Herman, "Evolution of the universe," Nature **162**, 774–775 (1948).

[21] R. A. Alpher and R. C. Herman, "Remarks on the evolution of the expanding universe," Physical Review **75**, 1089–1095 (1949).

[22] G. Gamow, *The Creation of the Universe* (Viking Press, New York, revised edition, 1961), pp. 42–43.

[23] A. K. T. Assis and M. C. D. Neves, "History of the 2.7 K temperature prior to Penzias and Wilson," Apeiron **2**, 79–84 (1995).

[24] A. K. T. Assis and M. C. D. Neves, "The redshift revisited," Astrophysics and Space Science **227**, 13–24 (1995). This paper was also published in *Plasma Astrophysics and Cosmology*, A. L. Peratt (ed.), (Kluwer Academic Publishers, Dordrecht, 1995), pp. 13-24.

[25] A. K. T. Assis and M. C. D. Neves, "Die Rotverschiebung, neu bewertet." Translated from the English by M. Pohl. Available at `<https://www.ifi.unicamp.br/~assis/>`, (2013).

[26] A. K. T. Assis and M. C. D. Neves, "Geschichte der 2,7-K-Temperatur vor Penzias und Wilson." Translated from the English by M. Pohl. Available at `<https://www.ifi.unicamp.br/~assis/>`, (2013).

[27] A. K. T. Assis and M. C. D. Neves, "O desvio para o vermelho revisitado," in O. Freire Jr. and S. Carneiro, editors, *Ciência, Filosofia e Política: Uma Homenagem a Fernando Bunchaft* (EDUFBA, Salvador, 2013), pp. 53–69.

[28] A. K. T. Assis and M. C. D. Neves, "A história da temperatura de 2,7 Kelvin antes de Penzias e Wilson," in E. T. César, T. C. Soares, R. F. Carneiro, M. A. Escher, and B. B. d. L. Duque, editors, *Ciência em Dia: Jornadas de Divulgação Científica — A Matemática Está em Tudo*

(Editora Livraria da Física, São Paulo, 2018), pp. 25–42.

[29] Translated by C. Roy Keys.

[30] That is, $T = 0\ K = -273.15°\ C$.

[31] Gustav Robert Kirchhoff (1824-1887) was a German physicist and his scientific contributions were mainly in the field of electrical circuits, spectroscopy, black-body radiation and elasticity theory. He is the author of two fundamental laws of the classical theory of electrical circuits and thermal emission. Guillaume may be referring here to Kirchhoff's 1859 paper:

> "[...] we can very easily prove, from the general principles of the mechanical theory of heat, that *for rays of the same wave length at the same temperature the ratio of the emissive power to the absorptive power is the same for all bodies*."

In 1860 Kirchhoff introduced the term "black body" with the following definition:

> The proof I am about to give of the law above stated, rests on the supposition that bodies can be imagined which, for infinitely small thicknesses, completely absorb all incident rays, and neither reflect nor transmit any. I shall call such bodies *perfectly black*, or, more briefly, *black* bodies.

[32] G. Kirchhoff, "Über den Zusammenhang zwischen Emission und Absorption von Licht und Wärme," Monatsberichte der Königlichen Akademie der Wissenschaften zu Berlin, aus dem Jahre 1859 **December**, 783–787 (1860).

[33] G. Kirchhoff, "On the relation between the radiating and absorbing powers of different bodies for light and heat," Philosophical Magazine **20**, 1–21 (1860).

[34] G. Kirchhoff, "Ueber das Verhältniss zwischen dem Emissionsvermögen und dem Absorptionsvermögen der Körper für Wärme und Licht," Annalen der Physik und Chemie **109** (2), 275–301 (1860).

[35] G. Kirchhoff, "Ueber den Zusammenhang zwischen Emission und Absorption von Licht und Wärme," in G. Kirchhoff, editor, *Gesammelte Abhandlungen* (Johann Ambrosius Barth, Leipzig, 1882), pp. 566–570.

[36] G. Kirchhoff, "Ueber das Verhältniss zwischen dem Emissionsvermögen und dem Absorptionsvermögen der Körper für Wärme und Licht," in Max Planck, editor, *Abhandlungen über Emission und Absorption* (Wilhelm Engelmann Verlag, Leipzig, 1898), pp. 11–36. Ostwald's Klassiker der exakten Wissenschaften, Vol. 100.

[37] G. Kirchhoff, "Ueber den Zusammenhang zwischen Emission und Absorption von Licht und Wärme," in Max Planck, editor, *Abhandlungen über Emission und Absorption* (Wilhelm Engelmann Verlag, Leipzig, 1898), pp. 6–10. Ostwald's Klassiker der exakten Wissenschaften, Vol. 100.

[38] G. Kirchhoff, "Emission and absorption," in W. F. Magie, editor, *A Source Book in Physics* (McGraw-Hill, New York, 1935), pp. 356–360.

[39] Wilhelm Carl Werner Otto Fritz Franz Wien (1864-1928), usually known as Wilhelm Wien, was a German physicist. In 1893 he used theories about heat and electromagnetism to deduce the so-called Wien's displacement law. This law states that the black-body radiation curve for different temperatures will peak at different wavelengths that are inversely proportional to the temperature. In 1911 he received the Nobel Prize in physics for his work on heat radiation.

[40] Benjamin Apthorp Gould (1824-1896) was an American astronomer who created the *Astronomical Journal* in 1849 and founded the *Argentine National Observatory* at Córdoba in 1868 and the *Argentine National Weather Service*. He was one of the pioneers in utilizing photography for the study of astronomy. Hamilton expressed Gould's formula with the following words: "each full magnitude would be the fifth root of 100 (about 2.512 times) brighter or dimmer than the next full magnitude." Note that this is just the mathematical formula for astronomical magnitudes proposed by Norman Pogson in 1856.

[41] T. W. Hamilton, *Our neighbor Stars including Brown Dwarfs* (Strategic Book Publishing, Houston, 2012), p. 8.

[42] G. C. Comstock, "Biographical Memoir Benjamin Apthorp Gould (1824-1896)," Biographical Memoirs of the National Academy of Sciences **17**, 153–180 (1922). Presented to the Academy at the Annual Meeting.

[43] N. Pogson, "Magnitudes of thirty-six of the minor planets for the first day of each month of the year 1857," Monthly Notices of the Royal Astronomical Society **17**, 12–15 (1856). Doi: 10.1093/mnras/17.1.12.

[44] William de Wiveleslie Abney (1843-1920) was an English astronomer, chemist and photographer. In 1882 he received the Rumford Medal. In 1896 he published a paper on the photographic values of moonlight and starlight compared with the light of a standard candle.

[45] W. d. W. Abney, "The photographic values of moonlight and starlight compared with the light of a standard candle," Proceedings of the Royal Society of London **59**, 314–325 (1896).

[46] William Hyde Wollaston (1766-1828) was an English chemist and physicist. In 1820 he was president of the *Royal Society*.

[47] Pierre Bouguer (1698-1758) was a French geophysicist and astronomer. In 1729 he published a work defining the quantity of light lost by passing through a given depth of the atmosphere. He compared the intensity of the light of the Sun with that of the Moon and made some of the earliest measurements in photometry.

[48] Johan Karl Friedrich Zöllner (1834-1882) was a German astrophysicist at Leipzig University. He created several photometers for the study of the Sun, Moon and the stars, which he called astrophotometers. In 1867 he made the first measurement of the Sun's apparent magnitude using a photometer of his own design which superimposed the image from a small telescope on the image from a reference lamp.

Errata of the paper by A. K. T. Assis and M. C. D. Neves, "Complete and commented translation of Guillaume's 1896 paper on the temperature of space", American Journal of Physics, Vol. 88, pp. 1140-1144 (2020). Doi: 10.1119/10.0001775.

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- The first line of the Abstract should read:

Charles Édouard Guillaume (1861-1938) was a Swiss physicist who received the 1920 Nobel

- Page 1141, first column, the third line from bottom to top should read:

zero, i.e., 273 °C below the temperature at which ice melts.[30]