Temperature and Special Relativity

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The character of temperature in special relativity has been something of a "perpetual problem", with four different attitudes expressed since 1907, as reviewed below.

The debate has been largely decoupled from considerations of measurements of the temperature of moving objects, as this is seldom done in practice. A notable exception is the assignment of a temperature to a distant astrophysical object on the basis of the wavelength $\lambda_{\rm peak}$ of the peak in its optical spectrum, if the (retarded) velocity $\mathbf{v}$ of the object with respect to the observer on the Earth is somehow known. First, for a Planck spectrum, we could say that the temperature of the object inferred directly from $\lambda_{\rm peak}$ (as measured in the rest frame of the observer) is,

$$T[\mathrm{K}] = \frac{2898}{\lambda_{\rm peak}[\mu\mathrm{m}]}\,. \tag{1}$$

Then, the peak wavelength $\lambda^\star_{\rm peak}$ at the source would be, according to the relativistic Doppler effect (sec. 7 of [1]),

$$\lambda^\star_{\rm peak} = \frac{\lambda_{\rm peak}}{\gamma(1 + v\cos\theta/c)}\,, \tag{2}$$

where c is the speed of light, $\gamma = 1/\sqrt{1 - v^2/c^2}$, and θ is the angle in the rest frame of the observer between (retarded) velocity $\mathbf{v}$ and the line of sight from the observer to the (retarded) position of the distant object. Finally, we infer that the temperature of the object in its rest frame is [53, 54, 55, 56],

$$T^\star = \frac{\lambda_{\rm peak}}{\lambda^\star_{\rm peak}} T = \gamma\left(1 + \frac{v\cos\theta}{c}\right) T. \tag{3}$$

As such, different observers in the same inertial frame would consider the distant object to have different temperatures (in the rest frame of the observers). That is, this example does not lead to the notion that a distant, moving object has temperature dependent only on the frame of the observer.

This supports fourth variant in the theoretical debate on the relation between T and $T^\star$ considered below.

1 $T = T^\star/\gamma$

The earliest statement of a relation between the temperature $T^\star$ in the rest frame of an object and its temperature T as observed in a frame where the object has velocity $\mathbf{v}$ was given in 1907 by von Mosengil (posthumously; a student of Planck) [2], and reaffirmed shortly thereafter by Planck [3] and by Einstein [4],

$$T = T^\star\sqrt{1 - v^2/c^2} = \frac{T^\star}{\gamma}\,. \tag{4}$$

This view was the "conventional wisdom" for almost 60 years,[1] although Einstein privately expressed doubts about it in 1952 [83].

In 1939, van Dantzig [12] published a theory of relativistic thermodynamics in which the inverse temperature appeared in a 4-vector, together with the velocity 4-vector, $u_\mu = \gamma(c, \mathbf{v})$ of a reference frame relative to the rest frame * of the system,

$$\rotatebox[origin=c]{180}{T}_{\mu} = \frac{1}{T}\left(1, \frac{\mathbf{v}}{c}\right) = \frac{1}{T^\star}\frac{u_\mu}{c} = \frac{\gamma}{T^\star}\left(1, \frac{\mathbf{v}}{c}\right), \tag{5}$$

with the implication that $T = T^\star/\gamma$. This was largely unnoticed at the time.[2,3]

After the alternatives discussed below emerged around 1965, the relation (4) was defended by [17, 20, 21, 26, 29, 31, 39, 40, 41, 47, 51, 58, 72, 73, 74, 75, 90, 91, 97, 104, 105, 117], with the latest of these published in 2019.

2 $T = \gamma T^\star$

A challenge to eq. (4) in the form of,

$$T = \gamma T^\star, \tag{6}$$

was published by Ott (posthumously) in 1963 [14], but was not immediately noticed. The independent publication by Arzeliés in 1965 [15] of the form (6) launched a controversy that continues to some extent even now. Supporters of eq. (6) include [19, 22, 23, 30, 32, 33, 45, 60, 63, 102, 109, 113], the most recent of which is from 2015.

It was argued in [33] that the form (5) should be associated with the velocity 4-vector, $u_\mu = \gamma\,(c, \mathbf{v})$, by the introduction of the temperature 4-vector,

$$T_\mu = T\left(1, \frac{\mathbf{v}}{c}\right) = T^\star\frac{u_\mu}{c} = \gamma T^\star\left(1, \frac{\mathbf{v}}{c}\right). \tag{7}$$

3 $T = T^\star$

That temperature is a Lorentz invariant was argued for a few years, starting in 1966, by Landsberg [35, 38, 43, 44, 49].[4] This view attracted a few supporters: [48, 50, 59, 68, 69, 88, 92, 114, 115, 118]. After 1970, Landsberg favored the fourth variant.

[1] For this era, we cite only [7]-[11].

[2] Several authors [33, 50, 79, 105, 110] have subsequently used the inverse-temperature 4-vector (5).

[3] van Dantzig's prescription could be applied to any scalar quantity $Q^\star$ measured in some rest frame, to define a 4-vector $Q_\mu = Q^\star u_\mu$. This was applied to the electromagnetic field energy $U^\star_{\rm EM}$ in a frame where the electromagnetic field momentum is zero (if such a frame exists) by Rohrlich [65]. For comments by the present author on this, see footnote 4 of [81] and footnote 8 of [103].

[4] Eckart stated that temperature is a Lorentz scalar in 1940 [13], but this seems to have attracted little attention.

4 Only $T^\star$ Is Well-Defined

Already in 1964, Marshall [16] argued against attempts to identify a unique temperature of a system according observers in a frame where that system is in motion.[5] This is now the most common view [34, 36, 42, 46, 52, 57, 61, 64, 70, 71, 76, 77, 78, 79, 80, 82, 85, 86, 87, 89, 96, 98, 107, 99, 108, 112, 119].

(Nov. 11, 2023) A simple argument in support of this view concerns a box of gas at temperature $T^\star$ in the rest frame of the box, where the distribution of average velocities of molecules in the box is isotropic. However, in a frame in which the box is in motion the velocity distribution is anisotropic, such that a scalar temperature T is not well defined in this frame.[6]

5 Reviews

Reviews of this topic include [63, 64, 67, 80, 84, 94, 100, 101, 110, 111, 115, 116, 120].

References

[1] A. Einstein, *Zur Elektrodynamik bewegten Körper*, Ann. d. Phys. **17**, 891 (1905),
http://kirkmcd.princeton.edu/examples/EM/einstein_ap_17_891_05.pdf
http://kirkmcd.princeton.edu/examples/EM/einstein_ap_17_891_05_english.pdf

[2] K. von Mosengil, *Theorie der stationären Strahlung in einem gleichförmig bewegten Hohlraum*, Ann. d. Phys. **22**, 867 (1907),
http://kirkmcd.princeton.edu/examples/statmech/mosengeil_ap_22_867_07.pdf

[3] M. Planck, *Zur Dynamik bewegter Systeme*, Sitzb. König. Preuss. Akad. Wiss., 542 (1907), http://kirkmcd.princeton.edu/examples/statmech/planck_skpaw_542_07.pdf
Also, Ann. d. Phys. **26**, 1 (1908),
http://kirkmcd.princeton.edu/examples/statmech/planck_ap_26_1_08.pdf
These papers are also noteworthy as containing the first indication of the nonzero quantum zero-point energy. Planck developed this theme further in [5, 6].

[4] A. Einstein, *Ueber das Relativitaetsprinzip und die aus demselben gezogenen Folgerungen*, Jahrb. Rad. Elec. **4**, 411 (1907),
http://kirkmcd.princeton.edu/examples/GR/einstein_jre_4_411_08.pdf
On the Relativity Principle and the Conclusions Drawn from It,
http://kirkmcd.princeton.edu/examples/GR/einstein_jre_4_411_08_english.pdf

[5] M. Planck, *Eine neue Strahlungshypothese*, Verh. Deutsch. Phys. Gesell. Berlin **13**, 138 (1911), http://kirkmcd.princeton.edu/examples/statmech/planck_vdpgb_13_138_11.pdf

[5] Apparently, Einstein had arrived at this view in 1952 [83].

[6] Another concept with a preferred frame is Bernoulli's law for motion of fluids with zero viscosity, which holds only in the frame where the fluid flow is everywhere steady [93].

[6] M. Planck, *Über die Begründung des Gesetzes der schwarzen Strahlung*, Verh. Deutsch. Phys. Gesell. Berlin **14**, 113 (1912),
http://kirkmcd.princeton.edu/examples/statmech/planck_vdpgb_14_113_12.pdf
Also, Ann. d. Phys. **37**, 642 (1912),
http://kirkmcd.princeton.edu/examples/statmech/planck_ap_37_642_12.pdf

[7] F. Jüttner, *Die Dynamik eines bewegten Gases in der Relativtheorie*, Ann. d. Phys. **35**, 145 (1911), http://kirkmcd.princeton.edu/examples/statmech/juettner_ap_35_145_11.pdf

[8] M. von Laue, *Das Relativitätsprinzip*, (Braunschweig, 1911), p. 172,
http://kirkmcd.princeton.edu/examples/GR/vonlaue_relativitat_11.pdf

[9] R.C. Tolman, *The Theory of the Relativity of Motion* (U. California Press, 1917), p. 159,
http://kirkmcd.princeton.edu/examples/GR/tolman_relativity_17.pdf

[10] W. Pauli, *Relativitätstheorie*, Enzyl. Math. Wiss. Vol. V, part II, no. 19, 543 (1921), sec. 46, http://kirkmcd.princeton.edu/examples/GR/pauli_emp_5_2_539_21.pdf
Theory of Relativity (Pergamon Press, 1958).

[11] R.C. Tolman, *Thermodynamics and Relativity*, Science **77**, 291 (1933),
http://kirkmcd.princeton.edu/examples/statmech/tolman_science_77_291_33.pdf

[12] D. van Dantzig, *On the Phenomenological Thermodynamics of Moving Matter*, Physica **6**, 673 (1939), http://kirkmcd.princeton.edu/examples/statmech/vandantzig_physica_6_673_39.pdf

[13] C. Eckart, *The Thermodynamics of Irreversible Processes III. Relativistic Theory of the Simple Fluid*, Phys. Rev. **58**, 919 (1940),
http://kirkmcd.princeton.edu/examples/statmech/eckart_pr_58_919_40.pdf

[14] H. Ott, *Lorentz-Transformation der Wärme und der Temperatur*, Z. Phys. **175**, 70 (1963), http://kirkmcd.princeton.edu/examples/statmech/ott_zp_175_70_63.pdf

[15] H. Arzeliès, *Transformation relativiste de la température et de quelques autres grandeurs thermodynamiques*, Nuovo Cim. **35**, 792 (1965),
http://kirkmcd.princeton.edu/examples/statmech/arzelies_nc_35_792_65.pdf

[16] T.W. Marshall, *Statistical electrodynamics*, Proc. Camb. Phil. Soc. **61**, 537 (1965), p. 544, http://kirkmcd.princeton.edu/examples/statmech/marshall_pcps_61_537_65.pdf

[17] A. Gamba, *Relativistic Transformation of Thermodynamical Quantities (Beware of Jacobians!)*, Nuovo Cim. **37**, 1792 (1965),
http://kirkmcd.princeton.edu/examples/statmech/gamba_nc_37_1792_65.pdf

[18] H. Arzeliès, *Sur le concept de température en thermodynamique relativiste et en thermodynamique statistique*, Nuovo Cim. B **49**, 333 (1965),
http://kirkmcd.princeton.edu/examples/statmech/arzelies_nc_49b_333_65.pdf

[19] W.G. Sutcliffe, *Lorentz Transformations of Thermodynamic Quantities*, Nuovo Cim. **39**, 683 (1965), http://kirkmcd.princeton.edu/examples/statmech/sutcliffe_nc_39_683_65.pdf

[20] A. Guessous, *Sur le fonction de distribution relativiste d'un gaz parfait et la definition cinétique de la température*, Compt. Rend. Acad. Sci. **260**, 6811 (1965), http://kirkmcd.princeton.edu/examples/statmech/guessous_cras_260_6811_65.pdf

[21] A. Guessous, *Sur la transformation relativiste de la température*, Compt. Rend. Acad. Sci. **261**, 1182 (1965), http://kirkmcd.princeton.edu/examples/statmech/guessous_cras_261_1182_65.pdf

[22] A. Børs, *Note on the temperature of a gas moving at relativistic speed*, Proc. Phys. Soc. London **86**, 1141 (1965), http://kirkmcd.princeton.edu/examples/statmech/bors_pps_86_1141_65.pdf

[23] T.W.B. Kibble, *Relativistic Transformation Laws for Thermodynamic Variables*, Nuovo Cim. B **41**, 72 (1966), http://kirkmcd.princeton.edu/examples/statmech/kibble_nc_41b_72_66.pdf

[24] A. Gamba, *Remarks to the Preceding Letter by Kibble*, Nuovo Cim. B **41**, 79 (1966), http://kirkmcd.princeton.edu/examples/statmech/gamba_nc_41b_79_66.pdf

[25] H. Arzeliès, *Comment on Dr. Kibble's Article*, Nuovo Cim. B **41**, 81 (1966), http://kirkmcd.princeton.edu/examples/statmech/arzieles_nc_41b_81_66.pdf

[26] R. Penney, *Note on Relativistic Thermodynamics*, Nuovo Cim. A **43**, 911 (1966), http://kirkmcd.princeton.edu/examples/statmech/penney_nc_a43_911_66.pdf

[27] T.W.B. Kibble, *Comment of the Remarks of Gamba*, Nuovo Cim. B **41**, 83 (1966), http://kirkmcd.princeton.edu/examples/statmech/kibble_nc_41b_83_66.pdf

[28] T.W.B. Kibble, *Comment of the Remarks of Dr. Arzeliès*, Nuovo Cim. B **41**, 83 (1966), http://kirkmcd.princeton.edu/examples/statmech/kibble_nc_41b_84_66.pdf

[29] R.K. Pathria, *Lorentz transformation of thermodynamic Quantities*, Proc. Phys. Soc. London **88**, 791 (1966), http://kirkmcd.princeton.edu/examples/statmech/pathria_pps_88_791_66.pdf

[30] R. Marchal, *Sur la formules de transformation de la chaleur et de la température en relativité restreinte*, Compt. Rend. Acad. Sci. A **262**, 982 (1966), http://kirkmcd.princeton.edu/examples/statmech/marchal_cras_a262_982_66.pdf

[31] L. de Broglie, *Sur la transformation relativiste de la quantité de la chaleur et de la température et la Thermodynamique cacheé des particules*, Compt. Rend. Acad. Sci. B **262**, 1235 (1966), http://kirkmcd.princeton.edu/examples/statmech/debroglie_cras_b262_1235_66.pdf

[32] A. Staruszkiewicz, *Relativistic Transformation Laws for Thermodynamical Variables with Application to the Classical Electron Theory*, Nuovo Cim. A **45**, 684 (1966), http://kirkmcd.princeton.edu/examples/statmech/staruszkiewicz_nc_45a_684_66.pdf

[33] L.A. Schmid, *Heat Transfer in Relativistic Charged-Fluid Flow*, Nuovo Cim. B **47**, 1 (1967), http://kirkmcd.princeton.edu/examples/statmech/schmid_nc_47b_1_67.pdf

[34] F. Rohrlich, *True and Apparent Transformations, Classical Electrons, and Relativistic Thermodynamics*, Nuovo Cim. B **45**, 76 (1966), http://kirkmcd.princeton.edu/examples/statmech/rohrlich_nc_45b_76_66.pdf

[35] P.T. Landsberg, *Special relativistic thermodynamics*, Proc. Phys. Soc. London **89**, 1007 (1966), http://kirkmcd.princeton.edu/examples/statmech/landsberg_pps_89_1007_66.pdf

[36] J.H. Eberly and A. Kujawski, *Relativistic Statistical Mechanics and Blackbody Radiation*, Phys. Rev. **155**, 10 (1967), http://kirkmcd.princeton.edu/examples/statmech/eberly_pr_155_10_67.pdf

[37] H. Arzeliès, *Note sur la thermodynamique relativiste*, Nuovo Cim. A **47**, 136 (1967), http://kirkmcd.princeton.edu/examples/statmech/arzelies_nc_a47_136_67.pdf

[38] P.T. Landsberg, *Does a Moving Body Appear Cool?* Nature **212**, 571 (1966), http://kirkmcd.princeton.edu/examples/statmech/landsberg_nature_212_571_66.pdf

[39] J.H. Fremlin, *Does a Moving Body Appear Cool?* Nature **213**, 277 (1967), http://kirkmcd.princeton.edu/examples/statmech/fremlin_nature_213_277_67.pdf

[40] P.D. Noerdlinger, *A Moving Body must "appear" Cool*, Nature **213**, 1117 (1967), http://kirkmcd.princeton.edu/examples/statmech/noerdlinger_nature_213_1117_67.pdf

[41] J.H. Eberly, *Temperature Transformations, a "Practical" Choice*, Nuovo Cim. B **48**, 167 (1967), http://kirkmcd.princeton.edu/examples/statmech/eberly_nc_48b_167_67.pdf

[42] I.P. Williams, *Temperature of a Moving Body*, Nature **213**, 1118 (1967), http://kirkmcd.princeton.edu/examples/statmech/williams_nature_213_1118_67.pdf

[43] P.T. Landsberg and K.A. Johns, *A Relativistic Generalization of Thermodynamics*, Nuovo Cim. B **52**, 28 (1967), http://kirkmcd.princeton.edu/examples/statmech/landsberg_nc_52b_28_67.pdf

[44] P.T. Landsberg, *Does a Moving Body Appear Cool?* Nature **214**, 903 (1967), http://kirkmcd.princeton.edu/examples/statmech/landsberg_nature_214_903_67.pdf

[45] C. Møller, *Relativistic Thermodynamics, A Strange Incident in the History of Physics*, Mat. Fys. Medd. Dan. Vid. Selsk. **36**, no. 1 (1967), http://kirkmcd.princeton.edu/examples/statmech/moller_kdvs_36_1_67.pdf

[46] I.P. Williams, *Does a Moving Body appear Cooler?* Nature **214**, 1105 (1967), http://kirkmcd.princeton.edu/examples/statmech/williams_nature_214_1105_67.pdf

[47] J.L. Redding, *Temperature of a Moving Body*, Nature **215**, 1160 (1967), http://kirkmcd.princeton.edu/examples/statmech/redding_nature_215_1160_67.pdf

[48] J. Lindhard, *Temperature in Special Relativity*, Physica **38**, 635 (1968), http://kirkmcd.princeton.edu/examples/statmech/lindhard_physica_38_635_68.pdf

[49] P.T. Landsberg and K.A. Johns, *The problem of moving thermometers*, Proc. Phys. Soc. London A **306**, 477 (1968), http://kirkmcd.princeton.edu/examples/statmech/landsberg_ppsa_306_477_68.pdf

[50] N.G. van Kampen, *Relativistic Thermodynamics of Moving Systems*, Phys. Rev. **173**, 295 (1968), http://kirkmcd.princeton.edu/examples/statmech/vankampen_pr_173_295_68.pdf

[51] K. Kuchař, *Transformation of Heat in Relativistic Thermodynamics*, Acta Physica Polonica **35**, 331 (1969), http://kirkmcd.princeton.edu/examples/statmech/kuchar_app_35_331_69.pdf

[52] R. Balescu, *Relativistic Thermodynamics of Moving Systems*, Physica **40**, 309 (1968), http://kirkmcd.princeton.edu/examples/statmech/balescu_physica_40_309_68.pdf

[53] C.V. Heer and R.H. Kohl, *Theory for the Measurement of the Earth's Velocity through the 3°K Cosmic Radiation*, Phys. Rev. **174**, 1611 (1968), http://kirkmcd.princeton.edu/examples/statmech/heer_pr_174_1611_68.pdf

[54] P.J.E. Peebles and D.T. Wilkinson, *Comment on the Anisotropy of the Primeval Fireball*, Phys. Rev. **174**, 2168 (1968), http://kirkmcd.princeton.edu/examples/statmech/peebles_pr_174_2168_68.pdf

[55] R.N. Bracewell and E.K. Conklin, *An Observer moving in the 3°K Radiation Field*, Nature **219**, 1343 (1968), http://kirkmcd.princeton.edu/examples/statmech/bracewell_nature_219_1343_68.pdf

[56] G.R. Henry *et al.*, *Distribution of Blackbody Cavity Radiation in a Moving Frame of Reference*, Phys. Rev. **176**, 1451 (1968), http://kirkmcd.princeton.edu/examples/statmech/henry_pr_176_1451_68.pdf

[57] L.G. Taff, *A relativistic transformation for temperature*, Phys. Lett. A **27**, 605 (1968), http://kirkmcd.princeton.edu/examples/statmech/taff_pl_27a_605_68.pdf

[58] S. Nakajima, *On Relativistic Statistical Thermodynamics*, Prog. Theor. Phys. **41**, 1450 (1969), http://kirkmcd.princeton.edu/examples/statmech/nakajima_ptp_41_1450_69.pdf

[59] G. Cavalleri and G. Salgarelli, *Revision of the Relativistic Dynamics with Variable Rest Mass and Application to Relativistic Thermodynamics*, Nuovo Cim. A **62**, 722 (1969), http://kirkmcd.princeton.edu/examples/statmech/cavalleri_nc_62a_722_69.pdf

[60] J. Bičák, *A Note on Relativistic Heat Engines*, Lett. Nuovo Cim. **1**, 302 (1969), http://kirkmcd.princeton.edu/examples/statmech/bicak_lnc_1_302_69.pdf

[61] R. Hakim and A. Mangeney, *Remarks on Relativistic Thermodynamics*, Lett. Nuovo Cim. **1**, 429 (1969), http://kirkmcd.princeton.edu/examples/statmech/hakim_lnc_1_429_69.pdf

[62] P.T. Landsberg and K.A. Johns, *The Lorentz Transformation of Heat and Work*, Ann. Phys. **56**, 299 (1970), http://kirkmcd.princeton.edu/examples/statmech/landsberg_ap_56_299_70.pdf

[63] L.A. Schmid, *Effects of Heat Exchange on Relativistic Fluid Flow*, NASA-TM-63499 (April, 1969), http://kirkmcd.princeton.edu/examples/statmech/schmid_nasa-tm-63499_69.pdf
A historical review starts on p. 59.

[64] C.K. Yuen, *Lorentz Transformation of Thermodynamic Quantities*, Am. J. Phys. **38**, 246 (1970), http://kirkmcd.princeton.edu/examples/statmech/yuen_ajp_38_246_70.pdf

[65] F. Rohrlich, *Electromagnetic Momentum, Energy and Mass*, Am. J. Phys. **38**, 1310 (1970), http://kirkmcd.princeton.edu/examples/EM/rohrlich_ajp_38_1310_70.pdf

[66] C.C. Habeger, *The Second Law of Thermodynamics and Special Relativity*, Ann. Phys. **72**, 1 (1972), http://kirkmcd.princeton.edu/examples/statmech/habeger_ap_72_1_72.pdf

[67] D. Ter Haar and H. Wergeland, *Thermodynamics and statistical mechanics in the special theory of relativity*, Phys. Rep. **1**, 31 (1971), http://kirkmcd.princeton.edu/examples/statmech/terhaar_pr_1_31_71.pdf

[68] H. Callen and G. Horwitz, *Thermodynamics and statistical mechanics in the special theory of relativity*, Am. J. Phys. **39**, 938 (1971), http://kirkmcd.princeton.edu/examples/statmech/callen_ajp_39_938_71.pdf

[69] O. Grøn *The Asynchronous Formulation of Relativistic Statics and Thermodynamics*, Nuovo Cim. B **17**, 141 (1973), http://kirkmcd.princeton.edu/examples/statmech/gron_nc_17b_141_73.pdf

[70] I. Paiva-Veretennicoff, *Is Gailiean Relativistic Thermodynamics Well Defined?* Physica **75**, 194 (1974), http://kirkmcd.princeton.edu/examples/statmech/paiva_physica_75_194_74.pdf

[71] D. Eimerl, *On Relativistic Thermodynamics*, Ann. Phys. **91**, 481 (1975), http://kirkmcd.princeton.edu/examples/statmech/eimerl_ap_91_481_75.pdf

[72] W. Israel, *Nonstationary Irreversible Thermodynamics: A Causal Relativistic Theory*, Ann. Phys. **100**, 310 (1976), http://kirkmcd.princeton.edu/examples/statmech/israel_ap_100_310_76.pdf

[73] N. Agmom, *Relativistic Transformations of Thermodynamic Quantities*, Found. Phys. **7**, 331 (1976), http://kirkmcd.princeton.edu/examples/statmech/agmon_fp_7_331_77.pdf

[74] H.-J. Treder, *Die Strahlungs-Temperatur bewegter Körper*, Ann. Phys. **34**, 23 (1977), http://kirkmcd.princeton.edu/examples/statmech/treder_ap_34_23_77.pdf

[75] H.-J. Treder, *Zur Strahlungstemperatur bewegter Körper*, Ann. Phys. **35**, 77 (1978), http://kirkmcd.princeton.edu/examples/statmech/treder_ap_35_77_78.pdf

[76] R.G. Newburgh, *Relativistic Thermodynamics: Temperature Transformations, Invariance and Measurement*, Nuovo Cim. B **52**, 19 (1979), http://kirkmcd.princeton.edu/examples/statmech/newburgh_nc_52b_219_79.pdf

[77] P.T. Landsberg, *Thought Experiment to Determine the Special Relativistic Temperature Transformation*, Phys. Rev. Lett. **45**, 149 (1980), http://kirkmcd.princeton.edu/examples/statmech/landsberg_prl_45_149_80.pdf

[78] P.A. Goodinson and B.L. Luffman, *The Relativistic Transformation Law for the Ideal-Gas Scale of Temperature*, Nuovo Cim. B **60**, 81 (1980), http://kirkmcd.princeton.edu/examples/statmech/goodinson_nc_60b_81_80.pdf

[79] W. Israel, *Thermodynamics of Relativistic Systems*, Physica A **106**, 204 (1981), http://kirkmcd.princeton.edu/examples/statmech/israel_physica_106a_204_81.pdf

[80] P.T. Landsberg, *Einstein and statistical thermodynamics I: relativistic thermodynamics*, Eur. J. Phys. **2**, 203 (1981),
http://kirkmcd.princeton.edu/examples/statmech/landsberg_ejp_2_203_81.pdf

[81] K.T. McDonald, *Stress and Momentum in a Capacitor That Moves with Constant Velocity* (Apr. 21, 1984), http://kirkmcd.princeton.edu/examples/cap_stress.pdf

[82] R. Aldrovandi and J. Gariel, *On the riddle of the moving thermometers*, Phys. Lett. A **170**, 5 (1992), http://kirkmcd.princeton.edu/examples/statmech/aldrovandi_pl_a170_5_92.pdf

[83] C. Liu, *Einstein and relativistic thermodynamics in 1952: a historical and critical study of a strange episode in the history of modern physics*, Brit. J. Hist. Sci. **25**, 185 (1992),
http://kirkmcd.princeton.edu/examples/statmech/liu_bjhs_25_185_92.pdf

[84] C. Liu, *Is There a Relativistic Thermodynamics? A Case Study of the Meaning of Special Relativity*, Stud. Hist. Phil. Sci. **25**, 983 (1994),
http://kirkmcd.princeton.edu/examples/statmech/liu_shps_25_983_94.pdf

[85] A. Komar, *Relativistic Temperature*, Gen. Rel. Grav. **27**, 1185 (1995),
http://kirkmcd.princeton.edu/examples/statmech/komar_grg_27_1185_95.pdf

[86] S.S. Costa and G.E.A. Matsas, *Temperature and relativity*, Phys. Lett. A **209**, 155 (1995), http://kirkmcd.princeton.edu/examples/statmech/costa_pl_a209_155_95.pdf

[87] P.T. Landsberg and G.E.A. Matsas, *Laying the ghost of the relativistic temperature transformation*, Phys. Lett. A **223**, 401 (1996),
http://kirkmcd.princeton.edu/examples/statmech/landsberg_pl_a223_401_96.pdf

[88] L. Avramov, *Relativity and Temperature*, Russ. J. Phys. Chem. **77**, S179 (2003),
http://kirkmcd.princeton.edu/examples/statmech/avramov_rjpc_77_S179_03.pdf

[89] P.T. Landsberg and G.E.A. Matsas, *The impossibility of a universal relativistic temperature transformation*, Physica A **340**, 92 (2004),
http://kirkmcd.princeton.edu/examples/statmech/landsberg_physica_a340_92_04.pdf

[90] G. Ares de Parga, B. López-Carrera and F. Angulo-Brown, *A proposal for relativistic transformations in thermodynamics*, J. Phys. A **38**, 2821 (2005),
http://kirkmcd.princeton.edu/examples/statmech/parga_jpa_38_2821_05.pdf

[91] T.K. Nakamura, *Covariant thermodynamics of an object with finite volume*, Phys. Lett. A **352**, 175 (2006), http://kirkmcd.princeton.edu/examples/statmech/nakamura_pl_a352_175_06.pdf

[92] D. Cubero *et al.*, *Thermal Equilibrium and Statistical Thermometers in Special Relativity*, Phys. Rev. Lett. **99**, 170601 (2007),
http://kirkmcd.princeton.edu/examples/statmech/cubero_prl_99_170601_07.pdf

[93] K.T. McDonald, *Is Bernoulli's Equation Relativistically Invariant?* Sept. 13, 2009),
http://kirkmcd.princeton.edu/examples/bernoulli.pdf

[94] D. Mi, H.Y. Zhong and D.M. Tong, *There Exist Different Proposals for Relativistic Temperature Transformation: The Whys and Wherefores*, Mod. Phys. Lett. A **24**, 73 (2009), http://kirkmcd.princeton.edu/examples/statmech/mi_mpla_24_73_09.pdf

[95] M. Requardt, *Thermodynamics meets Special Relativity — or what is real in Physics?* (Jan. 17, 2008), https://arxiv.org/abs/0801.2639

[96] G.L. Sewell, *On the question of temperature transformations under Lorentz and Galilei boosts*, J. Phys. A **41**, 382003 (2008), http://kirkmcd.princeton.edu/examples/statmech/sewell_jpa_41_382003_08.pdf

[97] C. Rasinariu, *Numeric Experiments in Relativistic Thermodynamics: A Moving System Appears Cooler*, (Oct. 10, 2008), https://arxiv.org/abs/0804.3836

[98] A. Montakhab, M. Ghodrat and M. Barati, *Statistical thermodynamics of a two-dimensional relativistic gas*, Phys. Rev. E **79**, 031124 (2009), http://kirkmcd.princeton.edu/examples/statmech/montakhab_pre_79_031124_09.pdf

[99] G.L. Sewell, *Statistical Thermodynamics of Moving Bodies*, Rep. Mod. Phys. **64**, 285 (2009), http://kirkmcd.princeton.edu/examples/statmech/sewell_rmp_64_285_09.pdf

[100] J. Dunkel, P. Hänggi and S. Hilbert, *Non-local observables and lightcone-averaging in relativistic thermodynamics*, Nature Phys. **5**, 741 (2009), http://kirkmcd.princeton.edu/examples/statmech/dunkel_np_5_741_09.pdf

[101] J. Dunkel and P. Hänggi, *Relativistic Brownian motion*, Phys. Rep. **471**, 1 (2009), Appendix C, http://kirkmcd.princeton.edu/examples/statmech/dunkel_pr_471_1_09.pdf

[102] F. Asenjo, C.A. Farías and P.S. Moya, *Statistical relativistic temperature transformation for ideal gas of bradyons, luxons and tachyons* (Mar. 5, 2009), https://arxiv.org/abs/0712.4368

[103] K.T. McDonald, *Lorentz Invariance of the Number of Photons in a Rectangular Cavity* (July 28, 2009), http://kirkmcd.princeton.edu/examples/uoveromega.pdf

[104] T.K. Nakamura, *Lorentz transform of black-body radiation temperature*, EuroPhys. Lett. **88**, 20004 (2009), http://kirkmcd.princeton.edu/examples/statmech/nakamura_epl_88_20004_09.pdf

[105] Z.C. Wu, *Inverse-temperature 4-vector in special relativity*, EuroPhys. Lett. **88**, 20005 (2009), http://kirkmcd.princeton.edu/examples/statmech/wu_epl_88_20005_09.pdf

[106] T.S. Bíró and P. Ván, *About the temperature of moving bodies*, EuroPhys. Lett. **89**, 30001 (2009), http://kirkmcd.princeton.edu/examples/statmech/biro_epl_89_30001_10.pdf

[107] J.J. Mareš *et al.*, *Relativistic transformation of temperature and Mosengeil-Ott' antinomy*, Physica E **42**, 484 (2010), http://kirkmcd.princeton.edu/examples/statmech/mares_physica_e42_484_10.pdf

[108] G.L. Sewell, *Note on the relativistic thermodynamics of moving bodies*, J. Phys. A **43**, 485001 (2010), http://kirkmcd.princeton.edu/examples/statmech/sewell_jpa_43_485001_10.pdf

[109] M. Przanowski and J. Tosiek, *Notes on thermodynamics in special relativity*, Phys. Scr. **84**, 055008 (2011), http://kirkmcd.princeton.edu/examples/statmech/przanowski_ps_84_055008_11.pdf

[110] T.K. Nakamura, *Three Views of a Secret in Relativistic Thermodynamics*, Prog. Theor. Phys. **128**, 463 (2012), http://kirkmcd.princeton.edu/examples/statmech/nakamura_ptp_128_463_12.pdf

[111] C.-Y. Wang, *Thermodynamics Since Einstein*, Adv. Nat. Sci. **6**, 13 (2013), http://kirkmcd.princeton.edu/examples/statmech/wang_ans_6_13_13.pdf

[112] G.W. Ford and R.F. O'Connell, *Lorentz transformation of blackbody radiation*, Phys. Rev. E **88**, 044101 (2013), http://kirkmcd.princeton.edu/examples/statmech/ford_pre_88_044101_13.pdf

[113] J.S. Lee and G.B. Cleaver, *Ultra-relativistic thermodynamics and aberrations of the cosmic microwave background radiation*, Mod. Phys. Lett. A **30**, 1550045 (2015), http://kirkmcd.princeton.edu/examples/statmech/lee_mpla_30_1550045_15.pdf

[114] J.J. Mareš, P. Hubik and V. Špička, *On relativistic transformation of temperature*, Fortschr. Phys. **65**, 1700018 (2017), http://kirkmcd.princeton.edu/examples/statmech/mares_fp_65_1700018_17.pdf

[115] W.M. Haddad, *Thermodynamics: The Unique Universal Science*, Entropy **19**, 621 (2017), Secs. 13-14, http://kirkmcd.princeton.edu/examples/statmech/haddad_entropy_19_621_17.pdf

[116] C. Farías, V.A. Pinto and P.S. Moya, *What is the temperature of a moving body?* Sci. Rep. **7**, 17526 (2018), http://kirkmcd.princeton.edu/examples/statmech/farias_sr_7_17526_18.pdf

[117] A.S. Parvan, *Lorentz transformations of the thermodynamic quantities*, Ann. Phys. **401**, 130 (2019), http://kirkmcd.princeton.edu/examples/statmech/parvan_ap_401_130_19.pdf

[118] N. Poplawski, *Invariant temperature of a moving body*, (Feb. 14, 2019), https://arxiv.org/abs/1902.05536

[119] L. Gavassino, *The Zeroth Law of Thermodynamics in Special Relativity*, Found. Phys. **50**, 1554 (2020), http://kirkmcd.princeton.edu/examples/statmech/gavassino_fp_50_1554_20.pdf

[120] J.A. Heras and M.G. Osorno, *A note on the relativistic temperature*, Eur. Phys. J. Plus **137**, 423 (2022), http://kirkmcd.princeton.edu/examples/statmech/heras_epjp_137_423_22.pdf