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.

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[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].

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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].

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[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].

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