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A Thermal Analogue of the Zel'Dovich Effect

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Abstract

We analyze in this work anisotropic heat conduction induced by a harmonically oscillating laser source incident on rotating conductors, exploiting an analogy with an effect discovered long ago, called the Zel'dovich effect. We re-covered the main results of a recently published paper that predicts the translational Doppler frequency shift of a thermal wave induced on a sample moving with uniform rectilinear motion. We extend then this framework to take into account the frequency shift of a thermal field propagating on a rotating platform. We show that it coincides with the rotational frequency shift which has been recently observed on surface acoustic waves and hydrodynamic surface waves, called rotational superradiance. Finally, we use an analogy with the Tolman effect to deduce a simple estimate of the average temperature gradient induced by rotation, showing the existence of a new cooling effect associated with heat torque transfer.

Keywords

Anisotropic Heat Diffusion, Chiral Spinning Thermal Waves, Heat Vortex Beams, Thermal Doppler Effect, Thermal Zel'dovich Effect, Thermal Polarization Vector, Rotation Induced Tolman Cooling Effect

1. Introduction

Since the formulation of the second law of thermodynamics in the middle of the eighteenth century from Kelvin and Clausius it became clear that control heat transport require has to be paid a cost, which is a part of the input energy in had to be lost irreversibly in the environment during a cycle of the heat machine. This solid empirical principle was formulated in the more general way by Carnot which took in account the unsuccessful experiments of a lot scientists which tried, unsuccessfully, to realize perpetum mobile; in fact he realized that the reason of their failure was that all known irreversible heat engines used to transform mechanical work into heat, using compressed fluids, has a parameter, the efficiency, that was always less than one and smaller than what could be reached in ideal reversible machine with the same maximum and minimum heat sources temperature. Anyway at the beginning of the nineteen century the discovery by Planck of its law focused most of the attention of the scientific community on the new quantum theory and, notwithstanding the experimental confirmation of the Poynting electromagnetic momentum, general tests of the thermodynamic principles were not conceived.

In particular, as far as we know, it was not studied in any laboratory the validity of the Carnot theorem with heat engines in rotating platform, transforming into heat not only mechanical work but even electromagnetic work. The problem of the validity of thermodynamics for a generic rotating accelerated observer is particularly urgent today not only because any laboratory is solidal to the rotating Earth, but even because it is necessary to understand modern fascinating unsolved questions in astrophysics and quantum thermodynamics. Therefore still today there is no well established theory of thermal conduction in non inertial frames since there are no experiments which can support or falsify a general covariant theory of thermodynamics. We remark that this theoretical question does not concerns only equilibrium thermodynamics but even quantum physics of condensed matter, since it is based on the postulate that the Fermi energy of electron band conduction is a frame invariant number, an hypothesis that till now has never been tested.

Notwithstanding in the thirties of the last century first Schiff and then in the sixties Irvine published new models on the electrodynamic laws in a rotating reference frames [1] [2], and Tolman discovered that a gravitational field induced a temperature gradient, analyzing more generally this effect with Ehrenfest [3] [4]; forty year after these two pioneer papers it was published the first theoretical investigation, as far as we know, on both the thermodynamics and the electrodynamics of a classical rotating probe was published by Zel' dovich [5] in 1971.

In fact this famous Russian astrophysics, inspired by theoretical speculations of Penrose on the thermal emission of a rotating black hole, discovered that the intensity of a monochromatic electromagnetic plane wave incident on a rotating conductor could be enhanced by over reflection, causing a negative energy transport of the electromagnetic wave propagating on its surface.

He deduced that this strange effect should happen whenever the transmitted wave on the surface satisfy the following inequality

$$\omega' = \omega - m\Omega < 0, \tag{1}$$

with ω the angular frequency of the electromagnetic beam, m an integer number associated to Bessel electromagnetic eigenfunction and Ω the angular frequency of the rotating conductor.

This relation predicts surface electromagnetic waves with negative frequency shift, which were interpreted, in analogy with the positron predicted by the Dirac equation, as waves that transport negative energy and induce a cooling effect on the rotating conductor. Unfortunately the value of the angular velocity Ω of the rotating conductor predicted to satisfy (1) was too high to be tested in amenable experiments and this strange phenomenon was forgotten. Recently different groups working on surface waves rediscovered the Zel'dovich effect, while they were looking for an acoustic analogue of it [6] [7] [8].

In fact it was possible to extend the original framework introduced by the Russian scientist to describe the propagation of surface acoustic waves with angular momentum propagating on a rotating platform with constant angular velocity; it has been detected a negative frequency shift, in accordance with (1), which has been confirmed for surface hydrodynamics waves too, showing the existence of a more general effect which has been called Rotational Superradiance [9].

Although the recent detection of acoustic rotational superradiance has experimentally confirmed the Zel'dovich effect, it is still lacking a microscopic dynamic model which explains the cooling effect on the rotating metal.

In this work we will describe translational and rotational thermal Doppler effect due anisotropic heat diffusion of vortex beams propagating on a rotating conductor and generated by a chopped laser beam, showing that they are chiral surface waves. In particular, assuming the validity of the Barnett effect and of the Nernst-Ettinghausen effect, we will deduce the existence of a thermal polarization vector, analogous to the standard Poynting one. We will predict a new effect that we call thermal Zel'dovich effect, which is a rotational frequency shift of the thermal waves propagating on the rotating conductor, showing that they are polarized and may transport and radiate angular momentum. We will then shows, generalizing the Tolman effect, that these new spinning thermal fields, predicted by our model, cause an average cooling effect on the surface of the rotating conductor, giving a rough estimate of it that might be tested in future experiments.

We will start generalizing the Fourier heat diffusion law [10] [11]

$$\boldsymbol{J} = -k\nabla T \tag{2}$$

with T the local temperature, k the thermal conductivity and $\boldsymbol{J}$ the thermal flux vector.

Our model is based on the assumptions that in a rotating conductive disk it is generated an effective magnetization current $\boldsymbol{M}_{rot}$, dependent on the temperature T and proportional to its angular velocity $\boldsymbol{\Omega}$, in accordance with the Barnett effect

$$\boldsymbol{M}_{rot}(T) = g(T)\boldsymbol{\Omega} = (1-\mu)\boldsymbol{B}_{rot} = (1-\mu)\mu\boldsymbol{H}_{rot}, \tag{3}$$

with μ the magnetic permeability of the conductor and $g(T)$ its temperature dependent girotropic tensor, which is simply a scalar number for an isotropic object.

Overmore we postulate that it is valid in the accelerated frame solidal to the rotating disk the Nernst-Ettinghausen effect, [12]; therefore we predict a non conservative thermal flux vector perpendicular to the effective magnetic field and to the temperature gradient defined by

$$\boldsymbol{J}_{rot} = L\boldsymbol{H}_{rot} \times \nabla T \text{ ,} \tag{4}$$

with L a phenomenological constant to be determined experimentally.

This new polar thermal flux vector implies that the Fourier diffusion equation must be generalized adding it to the second member of (2)

$$\boldsymbol{J} = -k\nabla T + \boldsymbol{J}_{rot} \text{,} \tag{5}$$

which, inserting (3), will be rewritten as

$$\boldsymbol{J} = -k\nabla T + b\boldsymbol{\Omega} \times \nabla T \text{ .} \tag{6}$$

This relation implies an anisotropic heat diffusion law induced by rotation given by

$$\boldsymbol{J} = -k\nabla T + \boldsymbol{J}_{rot} = -k_{ij}\left(\boldsymbol{\Omega}\right)\nabla T \text{ ,} \tag{7}$$

with k_{ij} the rotation dependent thermal conductivity tensor; we remark that this equation describes chiral heat vortex beams since, from(3) and (4) and (6) follows

$$rot\,\boldsymbol{J} \neq 0 \text{,} \tag{8}$$

and therefore

$$\oint \boldsymbol{J} \cdot \mathrm{d}\boldsymbol{s} \neq 0 \text{ ,} \tag{9}$$

which could be rewritten as a Bohr-Sommerfels quantized relation for spinning nanometals. We outline that the spinning thermal flux vector of (4) can be interpreted as a kind of an effective thermal Poynting vector, proportional to the thermal flux vector $\boldsymbol{J}$

$$\boldsymbol{S}\left(T\right) = \boldsymbol{E}_{rot}\left(T\right) \times \boldsymbol{H}_{rot}\left(T\right) \text{,} \tag{10}$$

once it is assumed the following definition of the non conservative electric field induced by rotation, in accordance with modern reformulation of Schiff theory [13],

$$\boldsymbol{E}_{rot}\left(T\right) = \boldsymbol{v} \times \boldsymbol{B}_{rot}\left(T\right) \text{,} \tag{11}$$

with $\boldsymbol{v}$ the velocity of the rotating conductor.

These relations (8) and (9), describe spinning chiral thermal waves propagating helicoidally on the surface of the rotating conductor which transport angular momentum.

Assuming the standard hypothesis of local conservation of energy, far from the focus of incident laser beam

$$div\,\boldsymbol{J} + \gamma \frac{\mathrm{d}T}{\mathrm{d}t} = 0 \text{ ,} \tag{12}$$

with γ the heat capacity per volume, we can deduce a self consistent equation containing as unique hidden variable the local temperature T, that is

$$k\nabla^2 T + b\,div\,\boldsymbol{\Omega} \times \nabla T = \gamma \frac{\mathrm{d}T}{\mathrm{d}t} \text{.} \tag{13}$$

This equation recovers the standard Fourier law when

$$div\boldsymbol{\Omega}\times\nabla T=0, \tag{14}$$

that is, if we introduce a thermal potential vector $\boldsymbol{A}$ such that

$$rot\,\boldsymbol{A}=\boldsymbol{\Omega}\times\nabla T, \tag{15}$$

whose physical interpretation will be discussed in a forthcoming paper.

If we extend, by the equivalence principle, the Luttinger theory [12] of local thermodynamic equilibrium in external gravitational fields to inertial fields induced, present on a rotating conductor, we have

$$\nabla\varphi_{rot}=-\frac{\nabla T}{T}, \tag{16}$$

fields to inertial fields induced by rotation, we can introduce a thermal polarization vector, describing heat waves transporting angular momentum

$$\boldsymbol{P}_T=-AT\boldsymbol{\Omega}\times\nabla\varphi_{rot}, \tag{17}$$

with A a phenomenological constant and v_T the phase velocity of the thermal wave.

This new thermal polarization vector describes chiral thermal waves with spin-momentum locking in accordance with a similar dynamics of general chiral surface waves discussed in a recent paper [14].

We hope that our proposal will stimulate investigation on the existence of the thermal polarization vector of (17), which we think might be applied in the future to control the directionality of heat transport by polarization.

In the following paragraph, we will focus this goal by analyzing the chiral thermal wave fields generated on a rotating platform by a harmonically oscillating laser heat source.

We will show, in particular, that is possible to deduce a negative frequency shift, which we will call thermal rotational Doppler effect. We will interpret it as a byproduct of heat beams transporting angular momentum, in analogy with spinning acoustic and hydrodynamics waves recently investigated [15].

The structure of the paper is the following: in the second paragraph we will discuss an old question debated originally by Planck and Einstein concerning the general meaning of the temperature of a moving body [16]. In the third paragraph we will illustrate briefly a previous model [17], published few years ago, which discussed a thermal analogue of the Doppler effect. In the fourth paragraph we will show how to deduce a rotational frequency shift for thermal fields propagating on rotating conductors, identical to those observed with acoustic waves which proved the existence of Rotational Superradiance.

Finally in the last paragraph, as we exposed previously, we will extend the Tolman effect [3] [4] to inertial fields present in a rotating frame to deduce a rough estimate of the cooling effect caused by harmonically oscillating laser sources incident on a rotating conductor, showing that new spinning thermal waves are polarized and may transport angular momentum.

2. Non Inertial Frames and Equilibrium Temperature

In this paragraph we will review very briefly an old controversy discussed more than one century ago by the founders of Quantum Physics, Planck and Einstein, which concerns the relativistic formulation of thermodynamics; they asked whether thermal equilibrium is a universal invariant property of a system, or on the opposite, was a local covariant one. We think that this debate is relevant for modern physics since it affects the validity of Stefan-Boltzman law and Kirchoff radiation law for moving heat sources.

In fact these two great scientists debated, after the discovery of the Planck law and the formulation of Einstein of Special Relativity, on the meaning of the equilibrium temperature of a body moving rectilinear with uniform velocity [16] and suggested that the temperature T and the exact differential heat transfer dQ should transform by a simple relativistic law

$$T = \gamma T', \quad dQ = \gamma dQ', \tag{18}$$

with γ the Lorentz factor, T' and dQ' the temperature and heat transfer seen by the moving observer (or of the moving conductor).

This relation, since it predicted that a moving body should look cooler, was strongly criticized by Ott, who proposed that it should look warmer by the opposite relation

$$T' = \gamma T, \quad dQ' = \gamma dQ. \tag{19}$$

Thirty years later Landsberg assumed that this thermodynamics quantity should be considered as Relativistic invariants [16].

Unfortunately, due to the very little value of the Lorentz factor, it was not possible to test none of them and most of statistical physics concluded that it was not possible to deduce a general transformation law of the equilibrium temperature of a moving body.

Therefore this deep theoretical question was abandoned during the seventies of the last century, notwithstanding its relevance in astrophysics; in fact the radiating power emitted by fast rotating stars is conventionally assumed to be proportional to the fourth power of the temperature in accordance with the standard Stefan-Boltzmann law.

On the contrary we think that it is still important to look for a definite transformation law of temperature measure by a moving observer and if it is still possible to define the equilibrium temperature of a conductor in a generic accelerated reference frame. We propose in this work that rotating inertial forces will break time reversal symmetry making impossible to have thermodynamic equilibrium in a rotating frame. Therefore we will explore in the next paragraph the out of equilibrium process of heat diffusion caused by a harmonically oscillating laser pulse, investigating whether it is possible to detect a thermal Doppler effect.

3. Translational Thermal Doppler Effect

As we illustrated in the previous paragraph it is not well known how the temperature of a moving conductor will appear to an observer at rest. Therefore we will investigate the more general problem of the way it looks a thermal wave field of a moving conductor to an observer at rest, assuming that for an harmonically oscillating temperature profile there will be a frequency shift analogous to the well known Doppler effect, which has been observed for a generic monochromatic wave such as electromagnetic, acoustic, elastic, and hydrodynamic.

We will resume in the following the first published model [17] which predicts a thermal Doppler effect for a sample moving rectilinear with uniform velocity. The authors of this work assumed that in the moving frame, solidal to the sample heat diffusion, could be described by the Wilson equation

$$\boldsymbol{J} = -k\nabla T + \rho C T \boldsymbol{V} \tag{20}$$

with ρ the mass density of the sample, C the heat capacity and $\boldsymbol{V}$ its velocity. Using the local law of energy flux conservation

$$div\,\boldsymbol{J} + \rho c \frac{\mathrm{d}T}{\mathrm{d}t} = w, \tag{21}$$

with w the laser power density, it is possible to deduce a generalized non Fourier law of heat diffusion given, far from the laser source, by the following parabolic equation

$$\nabla^2 T - \frac{\mathrm{d}T}{D\mathrm{d}t} - \frac{div(T\boldsymbol{v})}{D} = 0 \tag{22}$$

with D the thermal diffusivity, given by

$$D = \frac{k}{\rho C}, \tag{23}$$

assumed to be a scalar constant in every reference frame.

This relation can be rewritten just in one variable *x*, that is the direction of the moving sample, for a planar wave harmonically oscillating with angular velocity ω

$$\frac{\mathrm{d}^2 T}{\mathrm{d}x^2} - \frac{V_x}{D} - i\frac{\omega T}{D} = 0, \tag{24}$$

with V_x, the x component of the body velocity.

If we impose the boundary condition that the temperature vanishes at infinity, it can be shown that the general time independent solution of (24) is given by the following damped wave obtained by superposition of a forward wave (that is with x positive) and a backward wave (that is with x negative)

$$T(x,\omega) = A_+ \exp(\beta_+ x) + A_- \exp(\beta_- x), \tag{25}$$

with the wave number β given by the equation

$$\beta_\pm = \frac{V_x}{2D} \pm \sqrt{\left(\frac{V_x}{2D}\right)^2 + \frac{i\omega}{D}} \tag{26}$$

It can be shown that in the general case of source and sample moving in the same direction or in the opposite the Doppler frequency shift is given respectively by

$$\frac{\Delta\omega}{\omega} = \pm \frac{V_{O,S}}{\sqrt{2\omega D}} \sqrt{\frac{1}{2}\left(\sqrt{\gamma_s^4 + 4} - \gamma_s^2\right)}, \tag{27}$$

with the upper sign when they move towards, with $V_{O,S}$ the relative velocity between the observer and the source, and

$$\gamma_S = \frac{V_S}{\sqrt{2\omega D}}, \tag{28}$$

the ratio between the source velocity V_S and the phase velocity of the thermal wave

$$v = \sqrt{2\omega D}. \tag{29}$$

Even if the amplitude and phase wave fronts asymmetric plots predicted by the computer simulation of this model could be tested using the lock-in thermography technique, it seems very difficult to falsify the cumbersome relation (27) in the future.

One critical aspect of this model, we think, is that it derives a Doppler effect even if the temperature fields considered are not found by solving a real damped wave equation, as the well known telegraph equation [10].

We will show in the next paragraph that is possible to overcome the first objection by studying the rotational Doppler shift of surface thermal waves satisfying a generalized Wilson equation; then we will show that is possible to overcome even the second critique describing the propagation of new spinning surface thermal waves by a generalized telegraph equation.

4. Thermal Rotational Doppler Effect

During the sixties and the seventies of the last century in cosmology and astrophysics was rediscovered, as discussed in the introduction, the problem of thermal radiation emitted by a rotating conductive body, as a neutron star; since Maxwell equations and thermodynamic law were formulated and confirmed for static body it emerged the necessity to investigate how to extend both in rotating frames [13]. Apart from theoretical investigations the astrophysicists stimulated the experimental search of a rotational Doppler effect, trying to detect the rotational frequency shift of a rotating star. It was deduced a general simple equation for a planar monochromatic electromagnetic wave, that has been called by some authors a dynamical rotational frequency shift [18] [19], given by

$$\omega' = \omega - \Omega. \tag{30}$$

This relation has been confirmed recently even in non linear optics but it is still lacking a general deduction and experimental confirmation for acoustic, elastic and hydrodynamic waves. Curiously in the seventies of the last century, as we illustrated previously, another independent phenomena, which concerns radiation emitted by rotating source, has been discovered by Zel'dovich, which predicted a generalized rotational Doppler effect, described by the frequency shift given by (1).

This equation implies, due to the enhancement of the energy of the electromagnetic planar wave reflected by the rotating conductor, that the electromagnetic wave transmitted on the surface of the sample has negative frequency. This strange prediction was interpreted by the Russian physicist as the signature of a negative energy transport process associated to a cooling effect on the sample surface, but it is still, after 50 years since its discovery, a conjecture not supported by any empirical evidence. Anyway a lot of researchers working on structured waves investigated how to test this rotational super radiance effect for acoustic and hydrodynamic waves and, were very recently, published papers which confirmed it experimentally [8] [9].

We will show now that if we want to look for a thermal analogue of the Zel'dovich effect we must at first write the Wilson equation in polar coordinates in the reference frame solidal to the rotating platform, substituting the partial time derivative with the following convective time derivative,

$$D_t = \partial_t + \Omega\partial_\theta , \tag{31}$$

with ∂_θ the partial derivative with respect to the angular variable ϑ.

It is easy to show that just by substituting in the generalized equation in Equation (25) the spatial component $T(r,\theta,\omega)$ is a Bessel function of order m

$$T(r,\theta,\omega,t) = A\exp(\beta' r)\exp(im\theta)\exp(i\omega' t), \tag{32}$$

which satisfies the two dimensional Wilson Equation (22), in polar coordinates with the new frequency ω'

$$\omega' = \omega - m\Omega , \tag{33}$$

We remark that m implements the angular momentum of the helicoidal thermal waves with dispersion law

$$\beta'^2 - im\frac{\Omega}{D} - i\frac{\omega'}{D} = 0 \tag{34}$$

We remark that since the classical Doppler effect exists whenever there is a monochromatic wave with finite propagation speed, it would be theoretically more coherent to have a hyperbolic like wave equation with a well defined velocity of propagation.

We will therefore show in the following that the temperature profile given by (32) is a solution too of a generalized dissipative wave equation, called telegraph [11]

$$\frac{\mathrm{d}^2 T}{\mathrm{d}t^2} + \frac{\mathrm{d}T}{\tau \mathrm{d}T} - \frac{v^2}{n^2}\nabla^2 T = 0 , \tag{35}$$

with τ the relaxation time, and $v^2 = \frac{K}{\tau}$, the constant speed of propagation of the damped thermal wave, and the n the thermal index of refraction.

In fact just by substituting T given by (32), with (33) and (34), the Equation (35) is satisfied if n is a complex variable defined by

$$n^2 = \frac{K\beta'^2}{\tau\left(-\omega'^2 + \frac{i\omega'}{\tau}\right)} = \frac{K\left(im\frac{\Omega}{D} - i\frac{\omega'}{D}\right)}{\tau\left(-\omega'^2 + \frac{i\omega'}{\tau}\right)} , \tag{36}$$

describing absorption properties of the damped thermal waves.

Therefore, generally the particular solution (32) of the parabolic Wilson equation in the rotating frame can be put in correspondence with a damped thermal wave satisfying the generalized telegraph Equation (35), once we assume that rotation is equivalent to the presence of a non uniform medium which changes the heat wave speed of propagation (a thermal analogue of the Fresnel effect of light speed change in moving media).

5. Outlook and Perspectives

As we wrote in the introduction few years ago has been proved for the first time the rotational super radiant effect for acoustic and hydrodynamic waves, using in the experiments structured spinning waves as incident beams. Although similar experimental investigations are missing for thermal waves and heat transport, we hope that our model will stimulate experimental physicist to test in the future our theoretical prediction of new spin polarized thermal waves transporting negative energy and angular momentum. We think, it might be interesting to verify whether it is possible to control heat diffusion on rotating conductors by manipulating its polarization. In fact is possible to exploit the effective magnetic fields and electric fields introduced in Equations (3) and (11) to define a real thermal Poynting vector associated to the new spinning thermal waves, analogous to the standard one of electromagnetic waves

$$\boldsymbol{P}(T)=\frac{Re}{2}\boldsymbol{E}_{rot}(T)\times\boldsymbol{H}_{rot}(T), \tag{37}$$

without assuming the validity in a rotational reference of frame of the Luttinger Equation (16). We remark that this Poynting vector is parallel to the rotational velocity of the conductor and therefore implements, as we suggested previously, chiral thermal vortices with thermal Poynting spin vector identical to those of linearly polarized optical vortex beam [20]

$$\boldsymbol{S}(T)=\frac{Re}{2\omega'^2}rot\,\boldsymbol{E}_{rot}(T)\times\boldsymbol{H}_{rot}(T), \tag{38}$$

with ω' the angular frequency of the thermal wave given by (33).

Equation (38) implies that anisotropic heat diffusion on a rotating conductor may transport angular momentum and is the main new prediction of our work; we suggest that it could be observed indirectly looking for temperature dependent chiral forces generated by the over reflected spinning thermal radiation emitted by the rotating metal and, whenever observed, could be used in the future to induce cooling effects by thermal forces on chiral biomolecules as the D.N.A of bacteria.

We remind, in fact, that Zel'dovich suggested interpreting, electromagnetic transmitted waves with negative frequency as transporting negative energy due to a cooling effect. We will explain more in detail in a future paper how to deduce a general cooling effect associated with the propagation of thermal waves on a rotating conductor by a time-delayed D'Alembertian equation, which generalizes either the Wilson Equation (22) or the telegraph Equation (35). We want, finally, to illustrate how to deduce a naïve estimate of the average negative temperature gradient ΔT at the border of a rotating conductive platform, which could be tested in modern Laboratories and compared with a similar cooling effect caused by a rotating laser source investigated recently [21].

In fact if we assume the Equivalence Principle we can extend the validity of the Tolman effect to inertial fields, we can predict a cooling effect caused by a thermal wave incident on a rotating conductor by the following simple approximated relations

$$\nabla \ln\left(\frac{T}{T_0}\right) \cong -\left(\partial_r \varphi_{in}\right) v\tau \cong -\Omega^2 R v\tau \cong -\Omega^2 R\tau\sqrt{2\omega D}, \tag{39}$$

with T_0 the equilibrium temperature of the rotating disk environment and using as an estimate of the thermal speed of propagation the phase velocity given by (29).

If we insert in (39) the following experimentally amenable numerical values of the constants, that is $R = 1$ m, $D = 0.1$ m²/s, $M = 10$ kg, Ω = 50 Hz, $\omega = 1000$ Hz and assuming that the relaxation time is $\tau = 1$ ns, we deduce

$$\Delta \ln\left(\frac{T}{T_0}\right) \cong \ln\left(1+\frac{\Delta T}{T_0}\right) \cong -10^{-3}, \tag{40}$$

which, approximating at first order the logarithmic, for small average temperature gradients, gives

$$\frac{\Delta T}{T_0} \cong -10^{-3} \tag{41}$$

Although the average cooling effect predicted is a heuristic result based on rough approximations it is interesting because, contrary to the standard Tolman effect caused by gravitational forces, could be easily falsified or confirmed in Laboratories in the near future. This rotation induced cooling effect, we expect, should be balanced, by energy and angular momentum conservation laws, by the rotational kinetic energy transported by the angular momentum of the reflected thermal wave. We can therefore assume a radiation-conduction strong coupling process

$$K_{rad} + K_T + \frac{I\Omega^2}{2} = a = constant \tag{42}$$

with K_T the rotational energy of the surface thermal wave, K_{rad} the rotational kinetic energy emitted, transferring thermal torque due to the thermal Zel'dovich effect of spinning chiral thermal waves propagating on the rotating conductor.

We remark that this new rotational thermal effect concerns just the frequency shift of a surface monochromatic thermal wave transmitted on a conductor rotating with constant angular velocity; therefore it could be useful, we think, for future investigations on chiral thermal effects in astrophysics and to describe rotational quantum friction forces [22] [23] that, maybe in laser induced nuclear reactions of spinning nucleons.

We think that apart from astrophysics and quantum thermodynamics our framework might be useful to investigate the control of fission dynamics by chiral thermal forces [24], once it is developed a generalization of our model with temperature dependent index of refraction $n(T)$ and spinning thermal waves with a variable angular velocity $\Omega(t)$. We hope that this research goal might be stimulating for quantum physicists unsatisfied with the standard interpretation of Bell inequalities violations and more generally on the standard Copenhagen interpretation of quantum wavefunctions, since, so far, all Bell like test did' not considered thermal emission correlation effect induced by the detector photon absorption [25] [26].

6. Conclusions

We illustrate in this work a new model of anisotropic heat diffusion on rotating conductors which predicts a rotational Doppler effect for thermal waves propagating on a rotating conductor, which is the thermal analogue of what has been called the Zel'dovich effect. We showed that when the rotating metal absorbs a harmonically pulsated laser beam it is possible to deduce a rotational super radiance effect identical to what has been detected recently for spinning acoustic and hydrodynamic surface waves.

We interpret this new phenomenon as a cooling effect caused by spinning chiral thermal waves transporting negative energy. We deduced a simple estimate based on the Tolman effect and Equivalence Principle of the relative temperature gradient induced on the border of a rotating conductive platform exposed to a harmonically oscillating laser source, which could reveal, once tested experimentally, the existence of a new thermal polarization vector associated to heat torque transfer.

We discuss, finally, some applications of our thermal Zel'dovich effect in other fields of physics as astrophysics and quantum thermodynamics set up which might allow us to detect this cooling effect and chiral thermal forces in macroscopic and microscopic rotating systems.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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