Connections between thermodynamics, statistical mechanics, quantum mechanics, and special astrophysical processes

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This article discusses several diverse "zero-point" notions, ranging from early classical blackbody radiation analysis, to astrophysical and cosmological considerations now being contemplated. The now commonly accepted quantum mechanical meaning of "zero-point" is compared with the early historical thermodynamic meaning. Subtle points are then reviewed that were implicitly imposed in the early thermodynamic investigations of blackbody radiation. These assumptions prevented this analysis from applying to the situation when classical electromagnetic radiation does not vanish at temperature $T = 0$. These subtle points are easy to skip over, yet significantly change the full thermodynamic analysis. Connections are then made to some proposed mechanisms involved in various astrophysical processes. The possible connection with the observed increasing expansion of the universe is noted, and the increasing inclination of scientists to attribute this expansion to "vacuum energy." However, since the universe is not in a state of thermodynamic equilibrium, then the commonly accepted notion of "vacuum energy" or "zero-point" energy may not really be accurate. Altering this perspective may be helpful in coming to terms with the full physical description.

I. INTRODUCTION

The present article touches on a combination of several overlapping topics, with an attempt made to connect all these topics together at the end. To begin, a brief historical perspective is presented in Sec. II on the early meaning of "zero-point" (ZP), as in regards to the state of atomic systems near absolute zero temperature, and contrasted to the almost universal reference now used as the lowest quantized energy state of a system. A quantum mechanical perspective certainly provides a relation between these two concepts, but, as discussed here, the modern point of view is significantly different than the one first envisioned.

Such thoughts naturally lead one to examine the meaning of thermodynamic equilibrium, both from the more macroscopic perspective of conventional thermodynamics, but then as regards smaller and even "single" atomic systems in interaction with the infinite number of radiation modes. Such a discussion is indeed a fascinating one and requires a deep examination. Planck tackled aspects of these problems in his treatise in Ref. [1]. He introduced several devices for aiding the discussion of the thermodynamic behavior of radiation, such as a "black carbon particle" and rough scattering walls. His treatment of rays of heat radiation in a cavity included the concept that each ray could be described by a separate temperature, where the state of maximum entropy occurred when all rays were at the same temperature. Many of these concepts are still useful constructs today, and indeed can provide means for experimental testing in quantum cavity electrodynamics.

However, as discussed in Sec. III, some of these early ideas by Wien, Planck, and others, led to unnecessary restrictions on the thermodynamic analysis of electromagnetic radiation. Indeed, much of the early ideas implicitly restricted the Wien displacement analysis from applying to radiation that at absolute zero temperature did not reduce to zero radiation. These restrictions prevented the early analysis from being sufficiently general to take into account Casimir-like force considerations. These subtle points are easy to skip over, yet significantly change the thermodynamic analysis of a system.

This article ends by making some connections to mechanisms in proposed astrophysical processes involving the secular acceleration of particles, such as may be a contributor for cosmic ray formation. The possible connection with the observed increasing expansion of the universe is noted, and the increasing inclination of scientists to attribute this expansion to "vacuum energy." This brings the present discussion back full circle, by bringing in the notion that the universe is not in a state of thermodynamic equilibrium, so the commonly accepted notion of "vacuum energy," or "zero-point" energy, may not really be accurate. Altering this perspective should be helpful in coming to terms with the full physical description.

II. ZERO POINT

It is interesting to note the original historical meaning of "zero-point" as having to do with the observed nonvanishing kinetic energy of systems near the point of absolute *zero* temperature [2]. In contrast, the modern perspective and emphasis on the term "zero-point" is really quite different. Indeed, very often in the textbooks on quantum physics, as well as in the physics literature, the terminology of the "ZP state" and the "ZP energy" of a system is used interchangeably with the "ground state" and the "ground-state energy," without ever mentioning temperature or thermal equilibrium conditions [5]. Indeed, in keeping with this modern perspective, it's likely that most students in physics today directly associate ZP with the lowest ("*zeroth*") energy quantum state, rather than with the state of a system at *zero* temperature.

Now, of course, in the quantum mechanics (QM) perspective, the ground state is equivalent to the state of the system at $T = 0$, so technically, this viewpoint is certainly correct. In QM, the ground state of a physical system is the state with the lowest possible quantized energy level. We assume that the ground state of a system is nondegenerate, which is the usual assumption made.

Nevertheless, it is interesting to note that the thermodynamic significance of the ground state in QM plays a far less prominent role in the development of QM than does the property of quantization. Indeed, the thermodynamic role of the quantum-mechanical ground state is usually deduced as almost an afterthought, once the quantization of states is deduced, and the existence is established of a lowest energy level for the bound states of a system. Using statistical-mechanics notions, a thermal equilibrium state of the system at some temperature T is formed by taking an incoherent superposition of bound states, where the weighting factor is $\exp\left(-E_i/kT\right)$ for each quantized energy level E_i. As $T \rightarrow 0$, only the ground state remains in this summation, so that the ZP state is obtained.

III. IMPLICIT RESTRICTIONS IMPOSED IN BLACKBODY RADIATION ANALYSIS

A. Traditional thermodynamic blackbody radiation analysis

Here we will discuss how the implicit assumption entered the blackbody radiation analysis by early researchers around 1900 that as $T \rightarrow 0$, the electromagnetic thermal radiation spectrum in a cavity reduced to zero radiation. This assumption was certainly not explicitly made, but, was rather buried in other steps that resulted in this assumption being imposed. To emphasize the critical points, perhaps it is best to first review the steps that are traditionally followed in the derivation of the Stéfan-Boltzmann relationship [8]. Reviewing these points is very quick and enables one to rapidly get to the heart of the matter. Reviewing similar points for Wien's displacement law is also very helpful and revealing, although more complicated; hence, we will only touch on these points here. More detailed information can be found in Ref. [12]. In addition, a nice brief summary of the early historical work on the thermodynamics of radiation between 1859 and 1893, leading up to Planck's work, including the important work by Kirchhoff, Boltzmann, and Wien, is described in the first few pages of Ref. [3]. Planck covers the physical reasoning and assumptions behind this early work in beautiful detail in Parts I and II in Ref. [1].

If one considers a cylinder of volume V, with the walls of the cylinder maintained at temperature T, then blackbody radiation should exist within the cylinder. If one of the walls of the cylinder is taken to be a piston that can be moved, so as to change the volume of the cylinder, then work can be done as the piston is displaced. An apparently conventional thermodynamic analysis of this operation can then be carried out.

One key assumption made in this early work was that the radiation in the cavity was uniform and isotropic within the cavity. Part of the reasoning for this assumption was based on arguments advanced early on by Kirchhoff. Planck touched on these assumptions, recognizing that if the cavity was sufficiently small, or if the surface and any objects in the cavity had spatial variations on the order of the wavelength of the light within the cavity, then one could not use the reasoning and justifications first introduced by Kirchhoff for investigating the radiation properties at such wavelengths. Other than this acknowledgement [13], however, that their analysis cannot apply to small spatial dimensions, this early thermodynamic analysis does not go into any more real detail regarding these points.

Hence, one usually begins this analysis by assuming that the time average of the electromagnetic radiation energy is given by $U = Vu$, where V is the volume of the cavity or cylinder, and u is an electromagnetic energy density, that is independent of position within the cavity, and only dependent on temperature. Thus, U is taken to be an extensive thermodynamic quantity. The first law of thermodynamics is written as [14],

$$dU = d\left(Vu\right) = d'Q - PdV \quad , \tag{1}$$

where infinitesimal quasi-static processes are carried out, $d'Q$ is the heat flow *into* the cavity during such a process, $-PdV$ is the work done *on* the radiation in the cavity, and P is the radiation pressure on the piston.

A second key step followed in this traditional analysis is equating the radiation pressure P to $u/3$. Many references either simply note this point, or provide some rough reasoning to enable the relationship to be seen as reasonable. Planck in Ref. [1], Part II, Chap. I, shows the full reasoning that was initially put into establishing this relationship. He carried out the analysis of a plane wave incident at some angle to the normal of the plane conducting surface, where the material was taken to be composed of a perfect conductor that was nonmagnetizable. If one makes the further assumption that the density of plane waves incident on the plane surface is independent of direction, then one can show, as in Ref. [1], that $P = u/3$.

The second law of thermodynamics allows us to equate that $d'Q = TdS$, where dS is called the caloric entropy and is an exact differential. From Eq. (1),

$$dS = \frac{1}{T}\left[\frac{4}{3}udV + V\frac{du}{dT}dT\right] \quad . \tag{2}$$

Equating $\frac{\partial^2 S}{\partial T \partial V} = \frac{\partial^2 S}{\partial V \partial T}$, which is a consequence of the second law, then yields a simple first-order differential equation of $\frac{1}{T}\frac{du}{dT} = \frac{1}{T^2}4u$ that can be solved to yield the usual form of the Stéfan-Boltzmann relationship of [8]

$$u = \sigma T^4 \quad . \tag{3}$$

In addition to the above relationship, the other major thermodynamic work pertaining to blackbody radiation, prior to Planck's involvement, included Kirchhoff's analysis on absorptivity and emissivity, and the Wien displacement law. The latter, in particular, requires a fair bit of further analysis and includes the examination of how the spectrum of the radiation in the cylinder is altered as the piston is slowly pushed in or out. Wien's analysis took into account the Doppler shift that occurs to the radiation as the piston is quasistatically moved, resulting in the deduction that the spectral energy density must be of the following functional form:

$$\rho(\omega, T) = \omega^3 f\left(\frac{\omega}{T}\right) \quad , \tag{4}$$

where ω is the angular frequency of the radiation, and $\int_0^\infty d\omega \rho(\omega, T) = u(T) = \frac{1}{8\pi}\left\langle \mathbf{E}^2 + \mathbf{B}^2 \right\rangle$. Here, $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields of the radiation within the cavity, and the angle brackets represent a time or ensemble average.

Nevertheless, although Kirchhoff's and Wien's analyses are interesting and important, the above short review of the Stéfan-Boltzmann relationship is probably quite adequate for our present purpose, namely, to quickly get to the heart of the early thermodynamic analysis of blackbody radiation to examine what assumptions were implicitly made, in rather subtle ways, that resulted in the presence of electromagnetic ZP radiation being missed in the analysis. For those interested, however, Refs. [15] and [12] goes into the Wien displacement law in considerable more detail.

B. Subtle assumptions

Although it has taken some time for the following points to be recognized, the investigation into Casimir forces, begun in 1948 [16], [10], [17], [12] are what has now enabled the limitations of the early thermodynamic analysis to be better understood. As discussed in Refs. [15] and [12], a number of assumptions and steps were made in the early analysis that are not in general valid. One key point can immediately be brought out, namely, that the internal electromagnetic thermal energy of a cavity at temperature T was treated as being an extensive quantity that is proportional to the volume of the cavity ($U = Vu$). From the study of Casimir forces, and, indeed, from even the study of microwave resonators [18], [19], we know that this assumption is not in general valid. Part of the reason for this is that zero point radiation and Casimir forces necessarily involves the consideration of wavelengths of radiation that violate the restriction Planck states in Ref. [13], that "... the linear dimensions of all parts of space considered, as well as the radii of curvature of all surfaces under consideration, are large compared with the wavelengths of the rays considered." When considering the full thermal radiation spectrum, some frequency components of the radiation will always violate this restriction for any cavity. In a microwave resonant cavity, where the dimensions of the cavity are typically close to the wavelength of the radiation being manipulated, the electromagnetic energy density inside the cavity is certainly not a constant at all points in the cavity, but varies depending on the location in the cavity.

However, this point is only a part of the concern. Indeed, for cavities with good conducting walls, only a relatively small part of the total standing wave modes will violate the previous dimensional concern. For all the very high frequency modes, for which there are an infinite number, the wavelengths involved are all small compared to typical dimensions in a cavity. [Actually, this point is not quite true. If a cavity has sharp corners, such as in a rectangular parallelpiped, and if the surface is treated as being a continuum (as opposed to being composed of atoms), then the corners always violate the dimensional restriction [13] for any wavelength.]

Nevertheless, as we know from the study of Casimir forces, the electromagnetic ZP energy within a cavity violates the extensive property assumption. If a cutoff is not imposed [20], the electromagnetic energy within a cavity due to the presence of electromagnetic ZP radiation is infinite. However, the change in total electromagnetic energy due to a change in volume of the cavity is finite. Calculating this finite change in energy cannot be done by treating the total electromagnetic energy within the cavity as being equal to the volume V times an electromagnetic energy density u that is independent of the size and shape of the cavity. Rather, the full normal mode sum must be retained, and the difference in energy between the sum of normal mode energies due to the change in volume must be calculated, before continuum approximations are made [12].

Another simple way to recognize that the early thermodynamic analysis was not sufficiently general to include the situation that $\lim_{T\to 0} \rho(\omega, T)$ might not equal zero, or, that ZP electromagnetic radiation might exist, is the following: The piston surface was only explicitly calculated in the case of a perfectly reflecting surface [1], and, in that case, only when an isotropic and uniform radiation was assumed. Researchers then made the assumption that the pressure on other walls in the chamber were equal to this calculated value, independent of the material and relatively independent of the geometry of the wall. At the end of Sec. 66 in Ref. [1], Planck said, "... it may be stated as a quite general law that the radiation pressure depends only on the properties of the radiation passing to and fro [within the cavity], not on the properties of the enclosing substance [*i.e.*, the walls of the cavity]."

However, this statement is not really accurate, as can be understood when normal modes of radiation within a cavity and different boundary conditions demanded by different materials are taken into account [18], [19]. If we compare two cavities of the same shape and size, but made of different materials, the pressure in the two cavities are in general different, even when the walls of both cavities are held at the same temperature. For example, the Casimir force between two conducting plates is attractive, but between a perfectly conducting and an infinitely permeable plate, the force is repulsive [21]. Changing the shape of the cavity can change the magnitude and sign of the radiation force even more dramatically.

Of course, this difference in pressure from the one Planck refers to is really only largely noticeable when temperatures are sufficiently low and sizes sufficiently small, that is, when Casimir-related forces dominate over conventional thermal radiation pressure. Thus, although the theoretical importance of including the consideration of ZP radiation has numerous critical implications, to date the experimental importance has only been truly evident for sufficiently small cavities, at which point Casimir-like forces can become important. However, this brings up an even more noticeable point, namely, it is known that when parallel perfectly conducting plates are treated as continuous materials, then the radiation pressure due to the ZP radiation between the plates is formally infinite, as is the radiation pressure due to radiation impinging on the outside of the plates. The difference between the two is finite, however. The simple identification of $p = \frac{1}{3}\int_0^\infty \rho(\omega)\, d\omega = u/3$, with u treated as finite and independent of the shape, volume, and material wall properties of the cavity, is clearly inadequate for addressing such subtleties. Indeed, the early analysis only considered the radiation pressure from the inside of cylinder.

Now, Refs. [12] and [22] show how to adequately account for radiation pressure when Casimir related forces are present by taking into account the normal modes, and Ref. [12] shows the relationship of this expression to the energy density. Moreover, Ref. [23] deduces the relationship between this radiation pressure and the energy density for cavities of arbitrary shape and size, when the cavity walls are composed of perfectly conducting material.

Now let us turn to some specifics regarding the underlying mathematics that prevented the early thermodynamic analysis from being sufficiently general to include the consideration of ZP radiation. Perhaps the best way to make this point is to examine the force expression of Eq. (31) in Ref. [12] versus the electromagnetic energy expression of Eq. (37). It is then easy to see that $p \neq u/3$ in general, unless one follows the approximate reasoning surrounding Eq. (32) in that reference to make the connection.

However, it is also interesting to make a more direct connection with the original statements surrounding the early blackbody thermodynamic analysis. The lines after Eq. (96) in Ref. [1] read, in our present notation,

$$\begin{aligned}\triangle U &= \int_0^\infty d\omega\, \delta(Vu) = \frac{\delta V}{3}\int_0^\infty d\omega\, \omega \frac{\partial u}{\partial \omega} \\ &= \frac{\delta V}{3}\left\{ \left[\omega \rho(\omega, T)\right]\Big|_0^\infty - \int_0^\infty \rho(\omega, T)\, d\omega \right\} \quad . \end{aligned} \tag{5}$$

The first line in the above equation comes from Eq. (94) in Ref. [1], which was deduced as part of the Wien displacement analysis. The second line above was obtained via partial integration. This is the step that concerns us presently. In the paragraph that follows the above line in Ref. [1], Planck assumed that the first term above equals zero, which is an invalid assumption for ZP radiation [24]. Indeed, if we insert Planck's final result of Eq. (4), we explicitly see that the assumption is made that

$$\lim_{\omega\to\infty} f\left(\frac{\omega}{T}\right) = \lim_{\Theta\to\infty} f(\Theta) = 0 \quad . \tag{6}$$

If nonzero radiation is present at $T = 0$, the above limit should not equal zero .

C. Correcting analysis

The point of the present section of this article is not to go through all the details involved with generalizing the early blackbody thermodynamic analysis; much of this more detailed work was carried out in Refs. [15] and [12] (also see [23] for arbitrary cavity shapes with perfectly conducting walls). Rather, the intent here is simply to make the need and means for the required generalization more apparent. By doing so, the importance of including the concept of ZP radiation in thermodynamic analysis will be better brought out. We will then build on these points later in this article when examining recent observations and ideas concerning astrophysical phenomena.

Summarizing previous work then, just like the early blackbody thermodynamic analysis involved quasistatic displacement operations of a piston in a cavity, Refs. [25], [15], [12], [26], [27], [28], and [23] also involved quasistatic displacement operations. References [25], [15], [26], and [27] largely involved the quasistatic displacements of simple harmonic electric dipole oscillators that were in thermodynamic equilibrium with stochastic electromagnetic radiation. The consideration of van der Waals forces, at all distances (*i.e.*, including retardation effects), was taken into account here. Similarly, Ref. [12] most closely paralleled the early analysis by examining the displacement of two conducting parallel plates and a wall of a conducting parallelpiped, while taking into Casimir-like forces. References [23] and [29] extended much of this analysis to cavities of arbitrary shape.

The key steps in the analysis were somewhat similar to the early analysis outlined here in Sec. III A for the Stéfan-Boltzmann law, although considerably more involved. More specifically, the first law of thermodynamics was imposed, as in Eq. (1), but without the assumption of a uniform electromagnetic energy density. The ensemble average of the total internal energy was calculated for the fluctuating quantities involved, and the average work calculated for making a quasistatic displacement. The mathematics in the case of blackbody radiation, in Ref. [12], was actually considerably easier than the corresponding mathematics for the N oscillators considered in Refs. [25] and [15]. Restricting attention here only to the blackbody radiation analysis in Ref. [12], the real key here was to calculate internal energy and average forces involved by summing over all the normal modes of the radiation in the cavity, without imposing along the way that the radiation should somehow be independent of the material, shape, and size of the cavity walls.

The next step was then to impose a consequence of the second law of thermodynamics, namely, just as in the Stéfan-Boltzmann analysis reviewed earlier, that $d'Q = TdS$, where dS is an exact differential. In the case of two walls separated by a distance L [12], or in the more general case of an arbitrary deformation $\delta\mathbf{z}$ or displacement of section of a wall of an arbitrarily shaped cavity [23], one can require that $\frac{\partial^2 S}{\partial T \partial z_i} = \frac{\partial^2 S}{\partial z_i \partial T}$. The result is a first-order partial differential equation that must be satisfied by the radiation spectrum. The solution of this equation is satisfied by a functional form given by $\rho(\omega, T) = \omega^3 f\left(\frac{\omega}{T}\right)$[Eq. (4)]. We can call this relationship a generalized Wien displacement law, since the functional form is the same, but now the steps in the derivation also applies in the situation where the restriction of $\lim_{T\to 0} \rho(\omega, T) = 0$ is not imposed, so that the possibility of ZP radiation is taken into account.

Having gone through this analysis, which really does parallel the much simpler analysis for the original Stéfan-Boltzmann derivation in Sec. III A, now one can readily deduce what perhaps could be called a generalized Stéfan-Boltzmann relationship. Upon recognizing that the really important factor in physics are the changes and comparisons of systems, it then becomes clear that heat flow, work done on systems, and temperature changes are what really are observed and measured. For a volume V in free space, the change in thermal electromagnetic radiation energy in going from $T = 0$ to T is given by

$$U(T) - U(T=0) = V \int_0^\infty d\omega \left[\rho(\omega, T) - \rho(\omega, T=0)\right] = V \int_0^\infty d\omega \omega^3 \left[f\left(\frac{\omega}{T}\right) - \frac{\kappa}{c^3}\right] = \sigma T^4 V \quad , \tag{7}$$

where now $\sigma = \int_0^\infty d\Theta \Theta^3 \left[f(\Theta) - \frac{\kappa}{c^3}\right]$, takes into account the existence of ZP radiation, if $\kappa \neq 0$.

Further thermodynamic analysis can also be carried out, and has been for the case of dipole oscillators and cavity thermodynamics. In both cases, one can derive the functional form for ZP radiation, based on the thermodynamic definition of no heat flow at $T = 0$ during reversible thermodynamic operations [25], [12], [26], [28], [23]. Moreover, these systems were explored regarding the restrictions of the third law of thermodynamics, the requirement of a finite specific heat, and the ultraviolet catastrophe. In addition, one can examine other thermodynamic questions, such as whether extracting energy from ZP radiation violates any known physical laws [30], [31], [32]. Without question, work can be done on systems, or have systems do work, at or near $T = 0$; very large releases of energy are even possible if systems are taken out of thermodynamic equilibrium, so that irreversible processes ensue, either at $T = 0$, or at nonzero temperatures.

Thus, at this point it should be apparent that the early blackbody thermodynamic analysis contained some very innocuous and physically appealing assumptions that resulted in significant differences than what has been observed in nature. In particular, by not taking into account the possibility of electromagnetic ZP radiation in the analysis, effects such as due to Casimir-like forces and van der Waals forces could not be taken into account, and investigations on the Stéfan-Boltzmann law, the third law of thermodynamics, the ultraviolet catastrophe, specific heats, and other effects and properties, were significantly hindered in the early analysis.

IV. SECULAR ACCELERATION AND ASTROPHYSICAL PROCESSES

Having now gone over some of the subtleties involved with the early thermodynamic analysis, let us now turn to investigations largely led by A. Rueda [33], [34], [35]. These investigations involve what has been termed the possible "secular acceleration" [35] of charged particles due to the presence of electromagnetic ZP radiation. Charged particles bathed in thermal radiation are constantly being accelerated, as well as constantly radiating energy, due to the stochastic interaction nature of the particles and fields in equilibrium. Under thermal equilibrium conditions, and when $T > 0$, the average energy picked up due to the fluctuating impulses from the radiation should roughly average out to equal the energy loss due to a velocity dependent "drag" force. Einstein and Hopf first investigated these aspects [36]. Boyer noticed, however, that at $T = 0$, the usual "drag force" is necessarily absent, thereby leaving the effect of the fluctuating radiation impulses due to ZP radiation uncompensated [37], [38]. An average continual increase of velocity was then predicted, unless collisions with other matter occur to dissipate the increased kinetic energy.

Rueda subsequently proposed [33] that these effects might be observable in astrophysical processes. The extensive review in Ref. [34], and the more recent reference [35], contain relevant work and references related to Rueda's investigations. In particular, though, it seems possible that this "secular acceleration" mechanism may contribute, or even be a very important aspect of, phenomena such as cosmic rays, cosmic voids, and the observed X-ray and gamma ray backgrounds.

Thus, here we have yet another possible dramatic consequence of the existence of radiation being present at $T = 0$, *i.e.,* ZP radiation. Naturally such possible phenomena brings up many issues on whether basic thermodynamic concepts and laws are being violated, such as the first and second laws. These questions were investigated in Ref. [31]. The conclusion was that, no, if ZP radiation does indeed contribute to cosmic ray formation, then the secular acceleration phenomena should not violate either the first or second law of thermodynamics. Rather, the situation of "free" charged particles without a "container," situated in an environment with a near ZP-like spectrum, is really a system out of thermodynamic equilibrium. Indeed, if ZP-like fields are contributing to cosmic ray formation, then the particles being accelerating across the long "empty" (low mass regions) of intergalactic space, are clearly not in any sort of thermodynamic equilibrium with the matter they eventually encounter and strike. If secular acceleration is indeed the main contributor of cosmic rays, then the apparent free energy that has been acquired by these very high velocity particles is due to a finite change in the enormous amount of electromagnetic energy available in space. Energy can certainly still be conserved, as the kinetic energy picked up by the particles is lost by the radiation [27], [31], on average, but can be returned to the radiation upon the particle undergoing a deacceleration and colliding with other matter.

As for the second law, at first glance it does indeed appear to be violated if ZP radiation provides secular acceleration effects, as the particles appear to be, roughly speaking, extracting energy from a heat reservoir. Clausius' statement of the second law is [14], "No process is possible whose sole result is the transfer of heat from a cooler to a hotter body." However, a closer analysis of this phenomena reveals that this statement is not violated by this phenomena, since it is important to consider changes in thermodynamic equilibrium states. If one had a large enough container, so that the particles hit the walls, then it would be necessary to examine many traversals of such a system to really contemplate a system in equilibrium. The secular acceleration effect really only has to do with the average behavior of particles at different points in their trajectory. Upon averaging over the trajectories, the particles both pick up and lose energy, via collisions, in a natural stochastic behavior that needs to be considered in its totality. This point, and related ones, are discussed in more detail in Ref. [31].

However, one point should be brought out that was not fully emphasized in Ref. [31]. At a certain level, we cannot just take one system at some temperature T, and another system at the same temperature T, and put them together, and expect there to be "no changes." This is somewhat contradictory to our intuition, since we have long learned the "zeroth law of thermodynamics," namely [14]: "Two systems in thermal equilibrium with a third are in thermal equilibrium with each other." Macroscopically, of course, that is what we see. For example, suppose we have a thermometer, or temperature gauge, and two substances. Suppose we can put the thermometer in either substance and never see a change in the thermometer's reading. We would then say that via the zeroth law, all three are at the same temperature.

However, two systems that can effect each other always have an interaction energy. Separate systems, nominally at some temperature, will change in subtle and sometimes not so subtle ways as they are brought into contact with each other. At the very least, a microscopic thermocouple or small thermometer will experience van der Waals or Casimir-like forces as it is brought close to a substance that is nominally at the same temperature. If we were to take an atomic force microscope probe, and have it "walk" around the surface of a cavity, where the probe and the walls of the cavity are all nominally at the same temperature, the probe will experience changes in forces as it moves closer and farther from the walls, and as it examines a wall of one material versus another. Contrary to what one might intuitively suspect, such a probe can distinguish the different types of material forming the walls of a blackbody cavity. This is a quite different situation than what Kirchhoff, Wien, and Planck [1] originally described in their analysis, where the radiation and radiation pressure were treated as being independent of the material of the walls of the cavity.

My reason for making these points is that it may be critically important to consider the concept of thermodynamic equilibrium as being the equilibrium state of systems in net equilibrium with each other. Probes, particles, radiation, etc., all need to be treated as part of the net system, and need to be analyzed as being in interaction with each other, even when they are in thermodynamic equilibrium with each other. Having a cavity of electromagnetic thermal radiation, without ionized atoms present in the cavity, can in many important ways be quite different than the situation where the ions are present, as we know from plasma studies. For systems not in thermodynamic equilibrium, the system is yet far more complicated. Extrapolating these ideas to the whole universe requires a careful examination of the basic assumptions, as will be discussed more in the following two sections.

V. INCREASING EXPANSION OF THE UNIVERSE

A fascinating phenomena has been observed and reported in recent years, that has attracted considerable attention in the astrophysical community. A major turning point occurred in 1998 [39], [40], when two teams of astrophysicists reported on new studies involving the luminosity of a particular type of supernova in nearby and distant galaxies. The results provided surprising evidence that not only is the universe not slowing down on its rate of expansion since the Big Bang, but the expansion is actually increasing in its rate.

In addition, very recent reports this year on the mappings of tiny fluctuations in the cosmic microwave background from the experiments BOOMERanG (Balloon Observations of Millimeter Extragalactic Radiation and Geophysics) [41] and MAXIMA (Millimeter Anisotropy Experiment Imaging Array) [42], [43] have provided additional evidence that the universe is flat.

Thus, we now have several sets of confirming evidence that the universe is expanding, and apparently at an increasing rate. However, the density of all visible matter and dark matter in the universe appears to be only about one third of what is needed to account for a flat universe, where expansion will continue forever. Many physicists are proposing that vacuum energy is a key component of the puzzle for understanding this phenomena. At a recent meeting of the American Astronomical Society (AAS 196, June 2000) in Rochester, N.Y., a team of astronomers reported they have new evidence for what makes up most of the mass of the universe, based on a survey of the redshifts of 100,000 galaxies. According to their analysis of this mapping of galaxies' redshifts, called the Two Degree Field (2dF) Galaxy Redshift, a universe composed of 2/3 vacuum energy contribution and 1/3 visible and dark matter contribution, would fit the observed astronomical data well [44].

VI. CONCLUDING COMMENTS ON THE STATE OF THE UNIVERSE AND "ZERO-POINT"

I will end this article with a few cautionary comments. In addition to well recognized microscopic phenomena, such as van der Waals and Casimir forces and the Lamb shift, which are commonly attributed to the effects of electromagnetic ZP radiation [10], [17], we have what appear to be very much macroscopic consequences of ZP fields. In particular, it appears that "zero-point" fields may play a role in astrophysical phenomena and cosmology. Without doubt, this comment is certainly speculative at this point, as both the theoretical and experimental aspects still require deeper investigation. However, an increasing number of physicists are beginning to examine the possible role of "ZP fields," particularly in light of the experimental data obtained during the past two years.

One reason for speaking with caution about the possible role of ZP fields in astrophysics is undoubtedly the one most frequently cited, namely, the famous cosmological constant problem [45]. Formally, the vacuum is supposedly infinite in energy, although most researchers feel there must be some sort of effective cutoff [20]. Nevertheless, even if huge, how one can reconcile the enormous energies to the ones needed to provide some gravitational effects, but not enormous ones, is by no means clear.

However, another reason for speaking with caution here, is one that I have not seen mentioned elsewhere, and which brings us back full circle to the initial discussion of this article on the thermodynamics of blackbody radiation. As mentioned in Sec. II, in quantum mechanics, "zero-point" is now commonly accepted as meaning the "zeroth," or lowest, quantized energy level of a system. In contrast, "zero-point" historically first referred to the properties of a system at absolute zero temperature. Specifying a temperature, even at $T = 0$, implies the system under discussion is in thermodynamic equilibrium. Our universe is not in thermodynamic equilibrium; indeed, in many ways, it is far from being in equilibrium. Thus, just as it was important to more carefully examine the meaning of ZP in the early classical analysis of blackbody radiation, so also it may be important to be careful regarding introducing "zero-point" notions in regard to the entire universe.

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