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COSMOLOGICAL CONSTRAINTS ON THE ZERO-POINT ELECTROMAGNETIC FIELD

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ABSTRACT

It has been argued by Boyer, McCrea, Puthoff, and others that the zero-point electromagnetic radiation of quantum theory really exists. This idea is examined from the cosmological viewpoint. If the field is regenerated on a cosmic scale, its energy density requires an unlikely combination of cosmological parameters. And if the field energy interacts gravitationally in the conventional way, it leads to some awkward cosmological consequences. General relativity appears to imply either that zero-point electromagnetic energy does not exist, or that it exists but does not gravitate. In either event, major revisions may be necessary in quantum mechanics and/or gravitation.

Subject headings: cosmic background radiation — cosmology — relativity

1. INTRODUCTION

It has been suggested in recent years that the zero-point electromagnetic energy apparently required by quantum theory is not an abstraction but is real. Boyer (1980a) has reviewed evidence for this, and McCrea (1986) has endorsed the view that so-called spontaneous transitions are in fact caused by unseen photons in a cosmological substratum. Puthoff (1989a) has put the issue on a firmer foundation by suggesting that the local energy density of the zero-point electromagnetic field is determined by an Olbers-type summation of the radiation from all the electrons in the observable universe. In what follows we shall examine the idea that the vacuum is actually a zero-point field. Despite the motivation for this idea from quantum theory, we shall find it runs into problems in cosmology as based on general relativity. It appears that these problems could only be avoided if it is assumed that zero-point electromagnetic energy does not interact gravitationally in the conventional way.

The real nature of the electromagnetic zero-point field (zpf) is one of the unanswered questions in the foundations of quantum electrodynamics (Barut 1980). The field arises by multiplying the density of normal modes ($\omega^2/\pi^2 c^3$) by the average energy of a mode at the absolute zero of temperature ($\hbar\omega/2$). Here as usual $\hbar = h/2\pi$ is the reduced value of Planck's constant, c is the speed of light, and ω is the angular frequency. We will use the regular frequency ν in place of the latter to aid comparison with astrophysical data below. In terms of this, the intensity of radiation in the interval ν to $\nu + d\nu$ is given by $i_\nu d\nu = (2h\nu^3/c^2)d\nu$, in units of ergs s^{-1} cm^{-2} sr^{-1} or similar. (The factor 2 here appears in astrophysical work like that of McCrea 1986 but not in quantum work like that of Puthoff 1989a, due to a difference in definitions, but we retain it here because we are interested in astrophysical applications.)

Multiplying by $4\pi/c$ gives the energy density in ergs cm^{-3} due to radiation from all directions (in the interval ν to $\nu + d\nu$) as

$$dE_\nu \equiv e_\nu d\nu = \frac{8\pi h}{c^3}\nu^3 d\nu . \tag{1}$$

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This spectrum has some remarkable properties, most of which can be adequately studied using a semiclassical approach in which h appears but where the equations are those of Maxwell. Extensive work of this type has been done by Boyer (1980a; see also 1980b; 1984a, b; 1975a, b; 1969; Henry & Marshall 1966). He has shown that equation (1) is the unique spectrum that is Lorentz invariant and invariant under an adiabatic compression or expansion. These properties are clearly relevant in cosmology.

In this context, it has been known for some time that for any spectral intensity i_ν Liouville's theorem implies that the quantity i_ν/ν^3 is conserved as photons propagate through space, so even though photons may be redshifted to produce different values of ν and i_ν, the ratio i_ν/ν^3 remains the same (Misner, Thorne, & Wheeler 1973). For the zpf cubic spectrum, therefore, at emission and observation we have $i_\nu^e/\nu_e^3 = 2h/c^2 = i_\nu^0/\nu_0^3$, and the spectrum has the same form. [Also, for an expansion of the universe between the times of emission and observation the energy densities (eq. [1]) are $dE_\nu^e = (8\pi h/c^3)\nu_e^3 d\nu_e$ and $dE_\nu^0 = (8\pi h/c^3)\nu_0^3 d\nu_0$ and have the same form; see McCrea 1986.] This is the background for the common statement that an isotropic zpf with $i_\nu = 2h\nu^3/c^2$ is seen as the same by all freely moving observers (Boyer 1980a; McCrea 1986; Puthoff 1989a).

For comparison, a redshifted blackbody spectrum with $i_\nu = 2h\nu^3/c^2(e^{h\nu/kT} - 1)$ also retains its form, but with an additional effect wherein the temperature changes such that $T_0/T_e = \nu_0/\nu_e = (1 + z)^{-1}$, where z is the redshift (see below). The quantity i_ν with units of ergs s^{-1} cm^{-2} sr^{-1} Hz^{-1} or similar is the prime measurable quantity in the study of cosmological radiation fields. A blackbody field is of course known to exist, with i_ν given to very high accuracy by the noted Planck function (Mather et al. 1990). No cosmological zpf with $i_\nu \propto \nu^3$ is known, but if it is a vacuum field, it may not be directly observable. However, it could have indirect effects such as ones involving cosmic rays (Rueda 1978, 1981, 1990; Rueda & Lecompte 1979). Also, according to conventional general relativity the energy given by equation (1) should have associated mass, so the zpf should have gravitational effects. It is these we will study below.

The main motivation for this is to help decide if the zpf is real or fictional. This is a fundamental question, about which workers in quantum theory and gravitation tend by and large to have opposite opinions. The view that the electromagnetic zpf is in some sense real has a number of adherents, notably Boyer (1980a), McCrea (1986), and Puthoff (1989a, 1987). The main points in favor of this view are that zpf fluctuations correctly account for the Casimir force between closely spaced metal plates, the van der Waals force between atoms, the Lamb shift of atomic spectral lines, and the stability against radiative decay of the electron in the hydrogen atom. It is also supported by recent observations of inhibited spontaneous emission from atoms between Casimir-type plates, which can be taken to mean that an atom must remain excited because some of the vacuum modes into which it would otherwise decay have been eliminated by the plates (Gabrielse & Dehmelt 1985; Hulet, Hilfer, & Kleppner 1985; see also Golden 1986). It has also been argued that the theory of spontaneous emission is most logical when couched in terms of a radiation-reaction field *and* a zero-point field (Milonni 1984). This combination can also explain the Casimir effect, though in this regard most of the physics comes from the radiation-reaction field while the vacuum field is mainly necessary for the formal consistency of the theory (Milonni 1982).

Other views of the Casimir effect involve self-energy and vacuum radiation pressure (Barut & Dowling 1987; Milonni, Cook, & Goggin 1988). However, the latter view involves a finite difference between two infinite numbers. And the fact the zero-point field has formally divergent energy suggests it may perhaps be better regarded as a formal artifice or subterfuge than a real physical thing. (See Milonni 1980 and Milton 1980; this is consistent with ideas of Jaynes and others.) Indeed, a common view is that while a vacuum electromagnetic field may be formally necessary for the consistency of the quantum theory of radiation, and while fluctuations of this make sense, the field itself is badly divergent in energy and should be viewed as an abstraction which can be ignored (see Bjorken & Drell 1964, 1965, and Heitler 1954; justification for this may come from extended theories of particle physics like supersymmetry, wherein zero-point energies cancel out exactly—Collins, Martin, & Squires 1989.) The fact that the electromagnetic zero-point energy (eq. [1]) is divergent when integrated over all frequencies can obviously be avoided by introducing a cutoff. But values of this derived from quantum theory lead to values of the zero-point density comparable to that inside an atomic nucleus. This is unacceptable from the viewpoint of standard gravitational theory and cosmology. Indeed, gravitational problems associated with the zpf have always been troublesome and led Pauli to deny its reality (see Enz 1974). The view that it is not real also avoids the issue of where such a field could originate, which until recently its advocates had not properly explained.

However, the suggestion of Puthoff (1989a) that the zpf may be an Olbers-type field is an improvement insofar as it allows a meaningful discussion of the origin of the radiation instead of it being simply set as an initial condition of the universe. He has shown that if the zpf exists, it can drive the motions of charged particles, which can in turn regenerate the field. The latter is in local equilibrium and preserves its characteristic cubic spectrum. He has used a model of a spatially flat universe whose matter consists of electrons and protons, where the former are mainly responsible for mediating the zpf because the role of the latter is suppressed (see below). This model is simple but interesting and deserves to be looked at carefully. In what follows, we will examine the Puthoff model for the zpf to see if it is compatible with conventional cosmology. However, our results will be seen to have generic implications for the question of whether a quantum zpf can be compatible with general relativity.

2. PROBLEMS WITH A COSMOLOGICAL ZERO-POINT FIELD

We will start by examining the mechanism of Puthoff (1989a) using an alternative calculation along the lines of one done for the intensity of intergalactic radiation by Wesson, Valle, & Stabell (1987) and Wesson (1991). We assume a uniform distribution of particles which can be described as a perfect fluid of density ρ and pressure p. The field equations of general relativity are then the familiar Friedmann equations:

$$8\pi G\rho = \frac{3kc^2}{R^2} + \frac{3\dot{R}^2}{R^2} - \Lambda\ , \tag{2.1}$$

$$\frac{8\pi Gp}{c^2} = -\frac{kc^2}{R^2} - \frac{\dot{R}^2}{R^2} - \frac{2\ddot{R}}{R} + \Lambda\ . \tag{2.2}$$

Here G is the gravitational constant, $k = \pm 1$ or 0 is the curvature constant, Λ is the cosmological constant, and $R = R(t)$ is the cosmological scale factor whose derivative with respect to cosmic time t is denoted by an overdot. Let one particle radiate in the interval ν to $\nu + d\nu$ at a rate $F(\nu, t)d\nu$ ergs s^{-1}, where for generality we do yet restrict the calculation to the case of a time-independent cubic spectrum.

Particles in a shell between comoving (Lagrangian) radii r and $r + dr$ contribute radiation at the origin (*us*) whose intensity is given by a product of three factors,

$$\frac{4\pi R^3 r^2\, dr}{(1 - kr^2)^{1/2}} \times n_0\left(\frac{R_0}{R}\right)^{\alpha} \times \frac{F(\nu, t)d\nu}{4\pi R_0^2 r^2(1 + z)^2}\ . \tag{3}$$

Here the first factor is the volume of the shell and depends only on the form of the Robertson-Walker metric that underlies equation (2) but not on the equation of state of the fluid of particles. The second factor is the number density of sources in the shell, in terms of the number density n_0 and scale factor R_0 at the present epoch t_0 of observation. It is larger than the current value by a positive power α of the ratio $R_0/R(>1)$, corresponding to the fact the radiation was emitted at an earlier time in the history of an expanding universe. The exponent α depends on the equation of state of the fluid. For a pressureless fluid (dust) with $p = 0$, no mass is lost or gained from a comoving volume element and $\alpha = 3$. For an expanding fluid with positive pressure, $\alpha > 3$. This can be seen most readily by recalling one of Einstein's equations for the general case of a spherically symmetric perfect fluid (Podurets 1964; Misner & Sharp 1964; Wesson 1986a). This says that if d is a distance measure defined such that $2\pi d$ is the circumference of a region of the fluid centered on the origin, then the mass m appropriately defined changes at a rate $\dot{m} = -4\pi p d^2 \dot{d}/c^2$. For a uniform fluid, a standard manipulation of equation (2) allows us to recover the conservation equation, which for the physically relevant case of a radiation-like equation of state $p = \rho c^2/3$ implies $\alpha = 4$. We will use $\alpha = 3$ to parallel Puthoff's calculation below, but use $\alpha = 4$ to look at another model later.

Returning to the factors that enter equation (3), the third is the intensity of the radiation emitted by a source at r and as observed by us. Note that the usual surface area term $4\pi R_0^2 r^2$ is augmented by two powers of the redshift term $(1 + z) \equiv R_0/R$ of the source. These relate to what Hubble called the number and energy effects. They are commonly included in general relativity implicitly by making use of an inverse-square intensity formula that involves luminosity distance defined as $rR_0^2/R = rR_0(1+z)$, where r is the coordinate distance (see, e.g., Lawden 1982). We have put these redshift terms into equation (3) explicitly, because if we follow McCrea (1986) in assuming zpf photons behave like ordinary photons, then the redshift terms $(1+z)$ in equation (3) can have a significant influence on the cosmological zpf intensity. However, *these redshift terms are absent from Puthoff's calculation, which therefore overestimates the intensity of the cosmological zpf.* (This can be seen to arise from a misunderstanding about coordinates in Puthoff 1989a: the radial coordinate in equation [20] of that paper should be identified with luminosity distance, not so-called proper distance defined by equation [21] or coordinate distance as implied.)

To proceed, it is convenient to replace the $(1+z)$ terms by R_0/R and to replace the r variable by the equivalent time t. This latter can be done as usual by using the equation for a radial null geodesic (light ray), which is $c\,dt = \pm R(1-kr^2)^{-1/2}\,dt$. Also, the frequencies at emission and receipt are related by $\nu/\nu_0 = R_0/R$, so ν can be replaced by $\nu_0 R_0/R$, and $d\nu$ can be replaced by $(R_0/R)d\nu_0$, since we are interested in the intensity in the interval ν_0 to $\nu_0 + d\nu_0$ as observed. Then the product (eq. [3]) becomes

$$cn_0 F\left(\frac{\nu_0 R_0}{R},\ t\right)d\nu_0\left(\frac{R}{R_0}\right)^{3-\alpha} dt\ . \tag{4}$$

The total intensity per unit observed frequency interval may be obtained from this by integrating over the period the sources have been in existence, say from $t = t_f$ (formation) to $t = t_0$ (now). Dividing by c, the corresponding energy density with units of ergs cm^{-3} Hz^{-1} or equivalent is

$$e_\nu = \frac{n_0}{R_0^{3-\alpha}} \int_{t_f}^{t_0} F\left(\frac{\nu_0 R_0}{R},\ t\right)R^{3-\alpha}\,dt\ . \tag{5}$$

This is a fairly general result and holds for any particle spectrum specified by F and any Friedmann model specified by R whose equation of state allows the density to be written as a power law in the scale factor with exponent α.

Let us now apply equation (5) to the Puthoff model, wherein electrons radiate a cubic spectrum in an Einstein–de Sitter universe. Let (m_e, m_p) be the masses of the electron and proton. Then the number density of electrons is the same as that of protons, so $n_0 = \rho_0/m_p$ where ρ_0 is the present mass density. Each electron absorbs energy from the zpf and reradiates it, with $F = 12\pi h\Gamma^2\nu^3$ where $\Gamma \equiv 2e^2/3m_e c^3$ in esu is the electron damping constant with units of seconds. (This form for F follows from multiplying the quantity given in Puthoff 1989a eq. [20] by $4\pi r^2 c$. Note that only electrons are considered in the Puthoff model, since the contributions of protons are a factor $[m_e/m_p]^2$ less and so may be neglected.) The cosmological model is the standard solution of equation (2) with $k = \Lambda = 0$, $R = t^{2/3}$, $\rho = 1/6\pi G t^2$, and $p = 0$. The last implies $\alpha = 3$ in equation (5), which now gives

$$\begin{aligned} e_\nu &= 12\pi h n_0 \Gamma^2 \nu_0^3 t_0^2 \int_{t_f}^{t_0} \frac{dt}{t^2} \\ &\simeq 12\pi h n_0 \Gamma^2 \nu_0^3 t_0^2 t_f^{-1} \quad (t_0 \gg t_f)\ . \end{aligned} \tag{6}$$

This form is different from that of Puthoff (1989a), notably in depending on t_f, the time of formation of the sources. But it is clear this must come in, because the field here and now must consist of contributions from remote sources that emitted their radiation long ago, and though these contributions are redshifted, they are dominated for the case of a simple ν^3 spectrum by high-frequency radiation emitted at early times. [For comparison, the blackbody spectrum $2h\nu^3/c^2(e^{h\nu/kT}-1)$ has its contributions from high redshift and early times sharply reduced by the exponential factor: seen Wesson 1991.] For the zpf to be cosmologically regenerated, the energy density (eq. [1]) $e_\nu = 8\pi h\nu_0^3/c^3$ of quantum theory must match the Olbers energy density (eq. [6]) of cosmology. They do of course match in form, as shown by Puthoff (1989a). But do they match in size? The answer is that they can always be made to do so by a judicious choice of the times t_0 and t_f. The former is constrained by observation, so the condition for equality of the energy densities per unit frequency interval is best couched as a condition on t_f, namely

$$t_f = (3/2)c^3 n_0 \Gamma^2 t_0^2\ . \tag{7}$$

For the Einstein-de Sitter model, we can take $t_0 = 1 \times 10^{10}$ yr, whence the solution implies $\rho_0 = 1 \times 10^{-29}$ g cm^{-3} and $n_0 = 5 \times 10^{-6}$ cm^{-3} approximately. (Also, $H_0 \equiv \dot{R}_0/R_0 = 2/3t_0 = 65$ km s^{-1} Mpc^{-1}. But it should be noted that while this is within observational bounds, it is well known that it is difficult to find a unique solution of equation [2] above that satisfies all astrophysical data unless one includes a significant cosmological constant [Gunn & Tinsley 1975; Tinsley 1978; Peebles 1986; Fukugita et al. 1990]. This parameter may in fact be time variable if it is related to a scalar field [Olson & Jordan 1987; Freese et al. 1987].) For ordinary electrons as sources, the damping constant defined above is $\Gamma = 6 \times 10^{-24}$ s approximately. With these data, t_f of equation (7) is about 2×10^7 yr. Now this may sound reasonable from the astrophysical standpoint, since at this time after the big bang the matter in the universe should indeed have been mainly protons and electrons rather than some exotic kind of particle to which the above analysis may not have applied. However, there is an objection involved, which is that *only for a certain choice of the source formation time does the Olbers field numerically match the zpf.*

This objection is a way of putting into focus a problem with the Puthoff model that is more general. The energy density of quantum theory (eq. [1]) depends on atomic parameters, while the energy density of cosmology (eq. [6]) depends on these plus astrophysical parameters. And the two can only match if the astrophysical parameters exactly satisfy eq. [7]. We have chosen to couch that equation as one for t_f, because it is the least certain; but the values for t_0 and n_0 are also uncertain, and the combination (eq. [7]) is a priori very unlikely.

This objection cannot be circumvented by simply using another model, even though solutions of equation (2) other than the one employed by Puthoff may have appeal. For example, one might consider a model in which the energy density of the zpf is greater than that of ordinary matter, so that the so-called hidden or missing mass could be identified with zero-point electromagnetic energy. (It will be seen below, however, that there are problems with models in which zero-point energy interacts gravitationally in the conventional way.) Now, the $k = \Lambda = 0$ solution of equation (2) with the ultrarelativistic or radiation equation of state $p = \rho c^2/3$ involves $R = t^{1/2}$ and $\alpha = 4$ in equation (5). But, it leads to the same equations (6) and (7), so although one may use different numerical values in the latter, the same conceptual problem exists. It is also present in the model of Puthoff (1989a), because in his analysis the Olbers field and the zpf only match if the particle density and radius of communication ($=3ct_0$ in the Einstein–de Sitter model) obey a certain relation. Puthoff correctly realized that such a relation is essential for the consistency of the hypothesis of a cosmologically regenerated zpf, but this does not explain where it comes from. Puthoff noted it could be related to the cosmological coincidences studied by Dirac and others, and these could conceivably arise as consequences of alternative theories of gravity like the one proposed by Puthoff (1989b). However, there are other explanations for these coincidences (Wesson 1978), and the effects involved in Dirac-type cosmologies can be explained by gravitational theories of other kinds (Wesson 1984, 1986b) that are more logical extensions of general relativity.

Before leaving the parameter-balance problem posed by equation (7), it should be mentioned that recent updates of the Puthoff model (Puthoff 1991; Santos 1991) imply equations similar to the ones given above, but justify equation (7) not as a condition on the source formation epoch but on the epoch (or equivalent distance) at which the zpf photons were last scattered. That there should be a last-scattering surface is in itself plausible, but that its epoch should have exactly the value required by equation (7) still seems to us implausible. In fact, in our view a tuning problem must arise in any model of the type being considered here, where an energy density that is basically quantum in nature has to be matched to one that is derived from an analysis based on general relativity.

In conventional general relativity, all energy has associated mass and gravity. Proponents of the electromagnetic zpf usually ignore this: the model of Puthoff (1989a) and the first one considered above consider the particles emitting the radiation, but not the latter itself, as sources of gravity. However, while it is possible to invoke a new principle whereby zero-point energy does not have mass, it is obviously more in keeping with the scientific method to assume that zpf photons are like other ones and ask if their energy can be constrained by gravitational effects.

Gravity is related to the total energy, so let us temporarily ignore the spectrum of the radiation emitted by a particle and consider its power $P(t) \equiv \int_0^\infty F(\nu, t)d\nu$. If we start from equation (3) again, but this time integrate over all wavelengths, we obtain the bolometric energy density

$$E = n_0 \int_{t_f}^{t_0} P(t)\left(\frac{R}{R_0}\right)^{4-\alpha} dt . \tag{8}$$

This has units of ergs cm^{-3} or similar, and is a different kind of function from that considered in equation (5) above. For the simplest case of constant-power sources (P_0) in an Einstein–de Sitter universe ($\alpha = 3$, $R = t^{2/3}$, $R_0 = t_0^{2/3}$ with $t_0 \gg t_f$) this radiation field has a mass density

$$\rho_r = \frac{3n_0 P_0 t_0}{5c^2} . \tag{9}$$

Since we are assuming the Einstein–de Sitter model, which strictly speaking has the equation of state of dust ($p = 0$), we must for consistency assume $\rho_r \ll \rho_0 = 1 \times 10^{-29}$ g cm^{-3} (see above). For the sake of illustration, let us assume $\rho_r = 1 \times 10^{-30}$ g cm^{-3}, with $n_0 = 5 \times 10^{-6}$ cm^{-3} and $t_0 = 1 \times 10^{10}$ yr as before. Then to maintain this field, equation (9) implies that each particle must radiate at a rate $P_0 = 1 \times 10^{-21}$ ergs s^{-1} approximately. We must now inquire about the source of this energy. Puthoff (1989a) has argued that the zpf is not a free field simply given as an initial condition of the big bang (like the cosmic blackbody background), but is instead generated by the motion of charged particles which in turn get their vibrational energy from the zpf. This sounds neat. However, we will see below that the energy density of the zpf must be finite to agree with cosmology, and in this case its energy density must decrease systematically due to the adiabatic expansion of the universe. That is, the ultimate origin of the zpf is merely pushed one step back by Puthoff's hypothesis, and we still need to account for its source of energy.

Now in the case of the usual intergalactic Olbers radiation, the source is the conversion of rest mass to radiation by stars. Can the conversion of particle rest mass also account for the zpf? Well, a power of $P_0 = 1 \times 10^{-21}$ ergs s^{-1} is a rate of change of mass $\dot{m}$ of about 1×10^{-42} g s^{-1}. Unfortunately, a steady change at this rate over the history of the universe would cause a particle to lose mass of order $\Delta m \equiv \dot{m} t_0 \simeq 3 \times 10^{-25}$ g, which is much larger than the mass of an electron 9×10^{-28} g. In other words, *a significant zpf cannot be accounted for by conversion of rest mass to energy, because the electrons would have radiated away all their mass by now.* An upper limit to the density of a zpf that can be generated from the rest masses of electrons can be obtained by putting $P_0 = m_e c^2/t_0$ in equation (9). Recalling that the number density and mass density of baryons are related by $n_0 = \rho_0/m_p$, this gives

$$\frac{\rho_r}{\rho_0} = \frac{3}{5}\frac{m_e}{m_p} . \tag{10}$$

This upper limit is somewhat dependent on the details of the model (we have followed Puthoff in assuming an Einstein–de Sitter solution with electrons as sources). But it is apparent that any model of this type will have difficulty in accounting for a zpf with a density high enough to be of cosmological significance.

This holds irrespective of the spectrum of the zpf, but if we now consider this then further problems emerge. The ν^3 spectrum (eq. [1]) diverges if the frequency is unbounded. An infinite energy density can of course be avoided by the introduction of a cutoff ν_c, but this destroys the Lorentz invariance of the spectrum. One can argue that this makes no practical difference if ν_c is very large, or alternatively if the cutoff wavelength λ_c is very small, perhaps of the order of the Planck length $(Gh/c^3)^{1/2} \simeq 4 \times 10^{-33}$ cm (Shupe 1985). But such a small λ_c is unacceptable if zero-point energy has mass and gravity associated with it, because the resultant density is enormous and would have led to a collapse of the universe when it was still very young. We can actually use the approximate validity of conventional cosmology to find a lower limit for λ_c, by requiring that the mass density of the zpf not exceed the critical (Einstein–de Sitter) density. By equation (1), this means

$$\frac{E_\nu}{c^2} = \frac{8\pi h}{c^5}\int_0^{\nu_c} \nu^3 d\nu = \frac{2\pi h \nu_c^4}{c^5} < 1 \times 10^{-29}\ \mathrm{g\ cm^{-3}} \tag{11.1}$$

or

$$\lambda_c > 0.2\ \mathrm{mm} . \tag{11.2}$$

However, a cutoff wavelength of order 1 mm or larger is not astrophysically acceptable. For example, it would destroy the Lorentz invariance of the zpf in a very practical way, and processes that are supposed to depend indirectly on the zpf would show cutoffs at easily accessible energies (Boyer 1980a;

McCrea 1986; Puthoff 1989a, b; Rueda 1978, 1981). Also, a cutoff at this size lies in the band occupied by the cosmic blackbody background, and even a tiny coupling between a high-density zpf and ordinary matter would result in a perturbation of the cosmic Planck spectrum for which there is no evidence (see Mather et al. 1990). A zpf with the critical density (eq. [11.1]) would energetically dominate the blackbody background, whose mass density is about 4×10^{-34} g cm^{-3}. The same goes for the galactic Olbers background, whose density is believed to be about 7×10^{-36} g cm^{-3}. These problems apply not only to the model of Puthoff considered above wherein the zpf is regenerated and coupled to ordinary matter, but also to models where the zpf is supposed to be a free field like the blackbody one that derives from the big bang. It is seen that the mass and gravity associated with the zpf restrict its density to very low values irrespective of its nature.

3. CONCLUSION

We have examined the viability of a real zero-point electromagnetic field as advocated by Boyer (1980a), McCrea (1986), Puthoff (1989a), and others by considering its cosmological implications. The self-regenerating Olbers-field model of Puthoff is attractive, but it appears to depend on a delicate choice of cosmological epoch, and it is not clear where the energy of the zpf ultimately originates. Unlike the intergalactic Olbers field derived from stars, the zpf can hardly be derived from conversion of the rest masses of particles. And if it is a field derived from the big bang, then the mass and gravitational effects associated with the zpf imply a cutoff in its spectrum that is awkward to reconcile with orthodox astrophysics. We have therefore confirmed in specific terms the widespread scepticism of workers in gravitation about the reality of the zpf.

However, many workers in quantum theory regard the zpf as a real and essential part of that subject. From this viewpoint, it is necessary to avoid the problems shown above. The simplest way to do this is to introduce the principle that zero-point energy does not gravitate. This could be because the photons it involves are virtual and do not have "time" to interact gravitationally with ordinary matter (see McCrea 1986). Another proposal is that zpf photons are real and have energy, but that this positive density field is canceled by a field of negative energy density. This could be quantum in nature, as mentioned before (Collins et al. 1989). But it could also be gravitational in nature, via a scalar field (Muslimov 1990) or a medium of negative mass (Bonnor 1989). If some kind of cancellation is involved and includes rest mass, it could be that the universe is described in a formal sense by the Milne model (the solution of eq. [2] with $k = -1$, $\Lambda = p = \rho = 0$, $R = t$). This is an intriguing possibility, since the Milne model does not have a horizon and therefore avoids the horizon problem. Whatever the eventual resolution of the nature of the electromagnetic zero-point field, major revisions may be required in quantum mechanics and/or gravitation.

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