Much Ado About Nothing: Applying a Metamaterial Model with Negative Energy to Address the Vacuum Catastrophe

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Abstract

The vacuum catastrophe remains one of the great enigmas of physics, with more than 50 orders of magnitude separating the observed nanojoule per cubic meter vacuum energy from the theoretical electromagnetic quantum vacuum energy density. Toward bridging this wide gap, we consider an unconventional model for the vacuum using hypothetical metamaterial foam including pockets having negative parameters and negative energy density. The proposed metamaterial properties are selected to preserve normal vacuum behavior after homogenization.

1. Introduction

The vacuum catastrophe remains one of the great unsolved problems in physics, where astronomical observations provide a measured vacuum energy density of $\sim\ 6.4 \times 10^{-10}$ J/m^3 compared to the predicted theoretical electromagnetic quantum vacuum energy density of $\sim\ 10^{114}$ J/m^3, with a ratio of $\approx 1.6 \times 10^{123}$ [1, 2]. More recently, the discrepancy has been reduced to 54 orders of magnitude in Martin [3]. This huge disparity suggests that any resolution of this problem is likely to require a substantial deviation from existing theory, rather than some modest adjustment to existing theory. We therefore investigate an unorthodox metamaterial model of vacuum, where vacuum is comprised of a metamaterial foam including pockets that have negative parameters and negative energy density.

2. Metamaterial Model of Vacuum

Our proposed model is in part motivated by "space-time foam" notions in certain quantum gravity models, and by earlier investigation of the role of dispersive "foamy" vacuum models in resolving observation of the late arrival of high-energy gamma rays in short gamma bursts [4, 5]. For our vacuum-catastrophe model, we similarly propose a "foamy" structure for the vacuum, where the vacuum is a metamaterial comprised of a mixture of regions having positive and negative permeability and permittivity (and possibly gain or loss) and positive and negative energy densities. The resulting proposed "foamy-vacuum metamaterial" (FVM) must exhibit the normal properties of vacuum, but with the added feature of eliminating the vacuum catastrophe error factor of $\approx 10^{54}$.

In one possible embodiment of the proposed FVM, the metamaterial foam illustrated in Fig. 1 can be comprised of sub-wavelength regions with negative relative permittivity $\epsilon_{rn} \ll 0$ and permeability $\mu_{rn} \ll 0$ embedded in a medium with relative permittivity $\epsilon_{rp} = 1 - \epsilon_{rn}$ and permeability $\mu_{rp} = 1 - \mu_{rn}$. For this example, if the negative regions occupy 50% of the volume, the effective permittivity and permeability of the composite would be $\epsilon_r = 1$ and $\mu_r = 1$ and equivalent to vacuum [6]. Here, the primary motivation for the new model is to divide space into an embedding positive index that contains regions of negative index, where the positive-index regions have very large positive energy densities and very large negative energy densities respectively. Such negative energy densities have been proposed by a number of investigators [7, 8]. Importantly, the average energy density at large scales can be much smaller than the local energy densities when the positive and negative densities nearly cancel each other. The primary motivation is that this model may then simultaneously support the lower energy densities associated with astronomical observations of $\sim\ 6.4{\times}10^{-10}$ J/m^3 along with localized high energy densities that may be associated with the $\approx 10^{54}$ larger quantum vacuum energy densities.

In the foregoing example, the overall medium should not suffer from dispersion issues, since $\epsilon_r = 1$ and $\mu_r = 1$. Although the model includes large local field energies, the total average energy at large scale would equal the observed zero-point or vacuum energy. In essence, passivity and energy conservation are taken to be phenomena applicable at larger scale. Depending on the nature of the underlying metamaterial unit cells and quantum concentrations, it

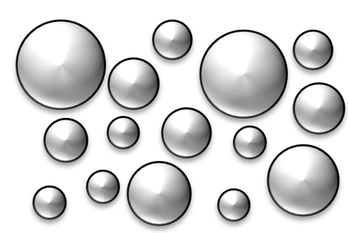

Figure 1: Illustration of vacuum metamaterial model. The foamy vacuum metamaterial model consists of subwavelength regions (illustrated as spheres above) with different relative permittivity and permeability than the embedding medium, such that the overall medium exhibits the normal vacuum parameters $\epsilon_r = 1$ and $\mu_r = 1$.

seems possible that the distribution of energies could be similar to Boltzman, Bose-Einstein, or Fermi-Dirac statistics, but somehow recast in a manner to properly accommodate local negative energy densities.

3. Field Energy Considerations

The primary goal of the proposed model is to provide the large energy densities in line with electromagnetic quantum vacuum energy, while retaining the low vacuum energy density at large scale, consistent with astronomical observations. In a region with no sources, Poynting's theorem is

$$\oint \mathbf{E} \times \mathbf{H} \cdot \partial s = -\int \left(\mathbf{E} \cdot \frac{\partial \mathbf{D}}{\partial t} + \mathbf{H} \cdot \frac{\partial \mathbf{B}}{\partial t} \right) \partial v \ . \qquad (1)$$

With $\mathbf{D} = \epsilon_{rp}\epsilon_\circ \mathbf{E}$ and $\mathbf{B} = \mu_{rp}\mu_\circ \mathbf{H}$, Poynting's theorem in the positive-index regions is then

$$\oint_p \mathbf{E} \times \mathbf{H} \cdot \partial s = \\ -\int \epsilon_{rp}\epsilon_\circ \mathbf{E} \cdot \frac{\partial \mathbf{E}}{\partial t} \partial v - \int \mu_{rp}\mu_\circ \mathbf{H} \cdot \frac{\partial \mathbf{H}}{\partial t} \partial v \ . \qquad (2)$$

Similarly, Poynting's theorem in the in the negative-index regions with $\mathbf{D} = \epsilon_{rn}\epsilon_\circ \mathbf{E}$ and $\mathbf{B} = \mu_{rn}\mu_\circ \mathbf{H}$ is

$$\oint_n \mathbf{E} \times \mathbf{H} \cdot \partial s = \\ -\int \epsilon_{rn}\epsilon_\circ \mathbf{E} \cdot \frac{\partial \mathbf{E}}{\partial t} \partial v - \int \mu_{rn}\mu_\circ \mathbf{H} \cdot \frac{\partial \mathbf{H}}{\partial t} \partial v \ . \qquad (3)$$

Finally, Poynting's theorem in a composite region (overlapping many spheres and their embedding regions in Fig. 1) with effective relative permittivitty and permeability $\epsilon_r = 1$ and $\mu_r = 1$ is simply given as in (1). As noted above, the proposed model is designed to support localized high energy densities within the spheres and within the embedding regions, as may be associated with the large quantum vacuum energy density. Furthermore, the model is also designed to simultaneously present the much lower average energy densities of astronomical observations within composite volumes comprised of both materials.

As a first approximation, suppose that the terms associated with the magnetic and electric field components are of similar proportion in (2) and (3). Next, let $\epsilon_{rn} \ll 1$, $\epsilon_{rp} = 1 - \epsilon_{rn}$, and $\mu_{rp}/\epsilon_{rp} = \mu_{rn}/\epsilon_{rn} = 1$. Then, to have the ratio of local energy density to large-scale energy density be $\approx 10^{54}$, would require $\epsilon_{rp} \approx -\epsilon_{rn} \approx 10^{54}$, and similarly $\mu_{rp} \approx -\mu_{rn} \approx 10^{54}$. The large-scale energy density over a large spatial volume would be $\approx 10^{54}$ times smaller, since $\epsilon_{rp} + \epsilon_{rn} = 1$ and $\mu_{rp} + \mu_{rn} = 1$ after homogenization over large regions.

Beyond the foregoing example, more complicated redistribution of local energies between electric and magnetic fields could be possible, but in even the most extreme redistribution of local electric and magnetic energy, at least one parameter would be of the order $\approx 10^{54}$. In addition, the results clearly do not depend on a 50% volume fraction. Lastly, retaining an average effective medium with $\epsilon_r = 1$ and $\mu_r = 1$ down to Planck scale may require the unit cells to be less than the Planck length of 1.5×10^{-35} m.

4. Conclusion

A metamaterial model for vacuum has been presented as a possible avenue to explain the $\approx 10^{54}$ ratio of theoretical and experimental energy densities known as the vacuum catastrophe. The model preserves the measured large-scale permittivity, permeability, and measured energy density of vacuum, while locally admitting energy densities $\approx 10^{54}$ larger than the large-scale average energy density.

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