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LETTER TO THE EDITOR

Quantum vacuum and virtual gravitational dipoles: the solution to the dark energy problem?

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Abstract The cosmological constant problem is the principal obstacle in the attempt to interpret dark energy as the quantum vacuum energy. We suggest that the obstacle can be removed, i.e. that the cosmological constant problem can be resolved by assuming that the virtual particles and antiparticles in the quantum vacuum have the gravitational charge of the opposite sign. The corresponding estimates of the cosmological constant, dark energy density and the equation of state for dark energy are in the intriguing agreement with the observed values in the present day Universe. However, our approach and the Standard Cosmology lead to very different predictions for the future of the Universe; the exponential growth of the scale factor, predicted by the Standard Cosmology, is suppressed in our model.

Keywords Quantum vacuum · Dark energy · Cosmological constant problem · gravitational dipole

1 Introduction

The nature of dark energy, invoked to explain the accelerated expansion of the Universe, is a major mystery in the theoretical physics and cosmology. From the purely mathematical point of view, adding a positive cosmological constant term to the right-hand side of the Einstein equation, can account for the observed accelerated expansion. However no one knows what is the physics behind such an ad hoc introduction of the cosmological constant. In principle, the cosmological constant Λ, may be interpreted as a cosmological fluid with a constant density (ρ_{de}) and negative pressure ($p_{de} = -\rho_{de}c^2$), i.e. $\Lambda = 8\pi G\rho_{de}/c^2$, but the physical nature of such a hypothetical fluid stays unknown.

The most elegant and natural solution would be to identify dark energy with the energy of the quantum vacuum predicted by the Quantum Field Theory (QFT); but the trouble is that QFT (for a classical Review see Weinberg 1989) predicts the energy density of the vacuum to be many orders of magnitude greater than the observed dark energy density and the corresponding cosmological constant:

$$\rho_{de} \approx 7.2 \times 10^{-27}\ \text{kg/m}^3, \tag{1}$$

$$\Lambda \approx 1.4 \times 10^{-52}\ \text{m}^{-2} \tag{2}$$

Summing the zero-point energies of all normal modes of some field of mass m up to a wave number cut-off $K_c \gg m$, QFT (Weinberg 1989) yields a vacuum energy density (with $\hbar = c = 1$)

$$\langle \rho_{ve} \rangle = \int_0^{K_c} \frac{k^2\sqrt{k^2+m^2}}{(2\pi)^2} dk \approx \frac{K_c^4}{16\pi^2} \tag{3}$$

or reintroducing $\hbar$ and c and using the corresponding mass cut-off M_c instead of K_c:

$$\rho_{ve} = \frac{1}{16\pi^2}\left(\frac{c}{\hbar}\right)^3 M_c^4 \equiv \frac{\pi}{2}\frac{M_c}{\lambda_{Mc}^3} \tag{4}$$

where λ_{Mc} denotes the (non-reduced) Compton wavelength corresponding to M_c. If we take the Planck scale (i.e. the Planck mass) as a cut-off, the vacuum energy density calculated from (4) is 10^{121} times larger than the observed dark energy density (1). If we only worry about zero-point energies in quantum chromodynamics, (4) is still 10^{41} times

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