International Journal of Theoretical Physics, Vol. 32, No. 8, 1993

Physical Implications of the Cosmological Constant

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Received October 28, 1991

The contribution of the quantum vacuum to the energy-momentum stress tensor in Einstein's field equations is very large. The observed cosmos is not in agreement with such a large term; thus, we require the presence of a cosmological constant to cancel this term. We discuss why this constant cannot originate from a quantum field or the gravitational field. We propose that this constant is physical evidence of the structure of space. The physical structure of space gives space an existence independent of the existence of matter and radiation.

The quantum mechanical vacuum energy is a physical fact with observable effects such as the Casimir effect (Weinberg, 1989). The energy density of the vacuum is very large and even diverges at short distances. The energy density of the vacuum due to the zero-point energies of all normal modes of a field contributes to the cosmological constant term. Since the observed cosmological constant is very small, the large contribution from the energy density of the vacuum needs to be canceled. In a review on the cosmological constant problem Weinberg (1989) points out five different approaches to the large cancellation problem. These approaches have yet to show the reasons for the impressive cancellation that must take place.

The cosmological constant is present in Einstein's gravitational field equation. If this constant is nonzero it will affect all the solutions of the gravitational field equation

$$R_{\mu\nu} - 1/2 g_{\mu\nu} R - \lambda g_{\mu\nu} = -8\pi G T_{\mu\nu}$$

where $T_{\mu\nu}$ is the energy-momentum tensor for matter, G is the gravitational constant that couples matter and gravity, $R_{\mu\nu}$ is the Ricci tensor, R is the scalar curvature, and λ is the cosmological constant. The tensor $T_{\mu\nu}$ con-

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0020-7748/93/0800-1441$07.00/0

tains a contribution from matter and radiation and a second contribution from the average energy of the vacuum,

$$T_{\mu\nu} = T_{\mu\nu}^{\text{matter}} + T_{\mu\nu}^{\text{vacuum}}$$

Since the average energy of the vacuum has the form $\langle \rho \rangle g_{\mu\nu}$, Einstein's equation can be written as

$$R_{\mu\nu} - 1/2 g_{\mu\nu} R - \lambda g_{\mu\nu} = -8\pi G T_{\mu\nu}^{\text{matter}} + 8\pi G \langle \rho \rangle g_{\mu\nu}$$

Thus, we obtain an effective cosmological constant $\lambda_{\text{eff}} = \lambda + 8\pi G \langle \rho \rangle$. The experimental limits on the value of the effective cosmological constant are nearly zero. Thus, an unnaturally large cancellation between λ and $8\pi G \langle \rho \rangle$ is necessary to achieve the observed upper bound (Chen and Wu, 1990).

In the absence of matter T^{matter} is zero everywhere. If we contract the indices in the Einstein equation we find that the scalar curvature R is given by

$$R = -4\lambda - 32\pi G \langle \rho \rangle$$

Therefore, if the cosmological constant λ cancels the vacuum contribution, then the scalar curvature of empty space can be zero. Otherwise, we will have a highly curved spacetime even in the absence of matter and radiation.

Space might be considered as a physical structure with internal forces that can give rise to the constant λ. The presence of these internal forces may be seen in Einstein's field equation. Consider a coordinate system that is comoving with matter; in the approximation matter fills space in a homogeneous and isotropic manner. In this coordinate system the term $\langle \rho \rangle g_{\mu\nu}$ behaves as a perfect fluid with positive energy density $\rho_{\text{eff}} = \langle \rho \rangle$ and negative pressure $p_{\text{eff}} = -\langle \rho \rangle$. If the cosmological constant is to cancel the action of $\langle \rho \rangle$, then $\lambda g_{\mu\nu}$ must behave as a perfect fluid with negative energy density and positive pressure. Thus, if the vacuum energy density produces an attractive force that tends to collapse the universe, the cosmological constant must produce a repulsive force that restores stability and vice versa. It seems that in an empty and flat space these two competing forces should be in equilibrium.

The energy of the vacuum is not constant, but diverges at high energies. In other words, at short distances there is an anomalous behavior in field theory. This problem reveals that our knowledge of space is incomplete. We propose that there is a physical internal structure of space that cancels the unwanted divergences. The cosmological constant reveals the presence of internal structure whose behavior is that of a perfect fluid with a given pressure and energy density, pressures or forces are the result of physical interactions. Thus, the origin of these physical effects may be in an internal structure of space.

Cosmological facts require that $\lambda_{\text{eff}} = \lambda + 8\pi G\langle\rho\rangle$ be zero or nearly zero. From quantum field theory we know that the vacuum energy of all matter and radiation has the same sign (Bjorken and Drell, 1985). The contributions from different fields do not cancel each other, but always increase the value of $\langle\rho\rangle$. If λ is to cancel $\langle\rho\rangle$, its sign must be opposite to the sign produced by a quantum field. Thus, λ cannot originate from a quantum field.

The gravitational fields are not a source for the cosmological constant either. The gravitational field varies from place to place, while λ by construction is a constant independent of the state of the gravitational field. Thus, λ could not be a function of the gravitational field.

We have so far found that the cosmological constant lacks direct relation with quantum or gravitational fields. Since no particle or field is a source for λ, the origin of this constant should be sought somewhere else. One thing that has not yet been considered as the origin of λ is space itself. If space is truly empty, this will be a meaningless consideration, but if space has a physical structure, λ should be a physical manifestation of it.

The Einstein equation for the gravitational field reveals that this field does not collapse in the absence of matter and radiation. When all matter is removed, there is always some kind of background gravitational field left. This background field describes spacetime as either flat or curved, depending on the cosmological constant term. It is not possible to imagine an object that has a physical property such as being flat or curved and lacks physical existence simultaneously. Thus, if we are to be consistent with the assumption that the Einstein equation properly describes spacetime, then spacetime must have a physical reality even in the absence of matter and radiation. In this paper we assume that there is a physical structure of spacetime that cannot be eliminated by removing all matter and radiation.

The structure of space takes now the role of a physical medium for the propagation of field excitations or particles (Einstein, 1983). The main contribution of this medium to Einstein's field equation is summarized by the Lorentz-invariant term $\lambda g_{\mu\nu}$. We assume that the physical components of the gravitational field describe the state of this medium.

If the spatial and temporal state of the medium is described by the physical content of the metric tensor $g_{\mu\nu}$, then the "ether drift" and related effects should not be present in this medium. We look at a Lorentz transformation as a rotation that involves space and time. A Lorentz rotation does not change the metric tensor $g_{\mu\nu}$ that summarizes the physical state of spacetime. Thus, if the medium has the 4-geometry described by $g_{\mu\nu}$, it will not be altered by a Lorentz transformation. This implies that physical facts such as the constancy of the speed of light are not violated in this medium.

Landau and Lifshitz (1975) realized the physical significance of a term such as the cosmological constant term and preferred to avoid it. It is enlightening to review what they said about the cosmological constant term: "We emphasize that we are talking about changes that have a profound physical significance: introducing into the Lagrange density a constant term which is generally independent of the state of the field would mean that we ascribe to space-time a curvature which cannot be eliminated in principle and is not associated with either matter or gravitational waves." In other words, the origin of the cosmological constant is not due to the presence of external particles or fields. Neither it is due to the dynamics of the geometry of spacetime. Its presence reveals profound physical facts.

If space has a physical structure, we expect to find many interesting effects. In particular, if we compare it to a crystal lattice, we may find several effects similar to those found in solid-state physics. It is necessary to find a proper interpretation of a particle in a physical space structure. Also, a physical structure for space implies that it is subject to the second law of thermodynamics.

In summary, the stability of spacetime requires that the large energy of the vacuum be canceled by a cosmological constant term. The origin of this physical constant cannot be other than space itself. This implies that space may have an internal physical structure.

"... all things were created through Him and for Him ... and in Him all things hold together." *Col.* **1**:16–17.

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