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Article

A Hint that Dark Energy Enables the Structure of Space

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Abstract

It is suggested that only a small fraction of the vacuum energy predicted by the standard model contributes to the cosmological constant with the remaining portion enabling the structure of space. For demonstration, a “nearly flat” spacetime is considered with a vacuum energy that partitions to both the observed cosmological constant (Λ) and to a much larger fraction ($\Delta\Lambda$) contributing to a Lagrange multiplier field introduced to preserve the relationship between observable spacetime and the metric tensor. Analysis of this Lagrange multiplier field offers a hint that the larger fraction ($\Delta\Lambda$) could in principle be observed in a minimum spatial distance predicted to be $(8\pi G\hbar/\Delta\Lambda c^3)^{1/4}$ which could have consequences on interpreting experiments that depend on very sensitive spatial measurements.

Keywords: general relativity; cosmological constant; quantization

1. Introduction

Assuming that the symmetry broken standard model ground state energy can be equated with dark energy and therefore is identified with the cosmological constant, a problem persists: the standard model predicts a cosmological constant of 10^{40} - 10^{120} times larger than its observed value.[1–3] While possible resolutions of the cosmological constant problem[1,4,5] have been proposed, there currently is no consensus on understanding its solution.[6] A summary can be stated as: “Most proposed solutions to the cosmological constant problem fall into three categories: change the general relativity (GR) equations that describe the expansion of the universe, modify the quantum field theory equations that predict the amount of vacuum energy, or throw something entirely new into the mix.”[7] Of course the simplest solution would be to assume that the cosmological constant is a fundamental constant of nature with a renormalized value equal to its observed value. This seems a bit contrived assuming that an initial regularization and renormalization are performed in the symmetric electroweak theory with a needed additional renormalization after symmetry breaking to adjust Λ to its observationally small value – in this case there is no prediction. We take a different approach using the Einstein equations with an added term that yields the familiar measurement condition as a constraint.[8] Observable spacetime then appears as an additional dynamical field, but not independent from the metric tensor. Quantization of these fields in a nearly flat spacetime seems to imply a large value for the cosmological constant with most of its contribution absorbed into the quantum structure of space. In the next section a familiar hydrodynamic analog is offered to clarify the context for later GR derived expressions. Then, in the same spirit as the analog, the inclusion of a Lagrange multiplier field in the GR action is shown to address the cosmological constant problem and to imply a quantization condition where a minimum spatial scale emerges. The last section summarizes and suggests an experimental consequence.

2. Hydrodynamic Analog

As a preliminary exercise, consider the $2d$ action for hydrodynamics in the Lagrangian point of view according to

$$S[\mathbf{x}, \lambda] = \int dT \int d^2 A \left\{ \frac{1}{2} \mathcal{M} \left(\frac{\partial \mathbf{x}}{\partial T} \right)^2 - \mathcal{M} U + \lambda \left[\rho \left(\frac{\partial x^1}{\partial A^1} \frac{\partial x^2}{\partial A^2} - \frac{\partial x^2}{\partial A^1} \frac{\partial x^1}{\partial A^2} \right) - \mathcal{M} \right] \right\} \quad (1)$$

where the $\mathbf{A}$ coordinates can be considered as the initial spatial coordinate labels that follow the material to any future position $\mathbf{x}$, and λ is a Lagrange multiplier field that preserves the continuity of flow. Also, ρ and $\mathcal{M}$ are mass densities in $\mathbf{x}$ and $\mathbf{A}$ space respectively where variations of Eq. (1) with respect to λ give a constraint that relates them. Assuming a local conservation of mass $\partial \mathcal{M} / \partial T = 0$, the Euler-Lagrange equations, in an Eulerian point of view, are the familiar hydrodynamic equations in $\mathbf{v}(\mathbf{x}, t) \equiv \partial \mathbf{x} / \partial T$:

$$\rho \left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right] = -\rho \nabla U - \nabla(\lambda \rho) \quad (2)$$

where $\lambda \rho$ can be identified as the pressure. The continuity equation can be derived from taking a time (T) derivative¹ of the constraint equation and is given by

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0. \quad (3)$$

As a simple system, imagine an expanding homogeneous material represented by $\mathbf{v} = H\mathbf{x}$ with the one measurable constant H . The Eq. (3) continuity then implies a density of $\rho = \rho_0 \exp(-3Ht)$. If the concept of pressure were unknown and excluded from Eq. (2), a potential energy could still be consistently inferred to be $U = -H^2 \mathbf{x}^2 / 2$. Now imagine that, independently, some microscopic model predicts a potential (analogous to the vacuum energy) with a much larger constant expressed as $U = -(H + \Delta H)^2 \mathbf{x}^2 / 2$. Returning to the basis of Eqs. (1-3), this would not be considered a controversial problem, instead it would imply the existence of a pressure given by the Lagrange multiplier field $\lambda = (H + \Delta H / 2) \Delta H \mathbf{x}^2$. Additionally, it would introduce independent measurable consequences. An interpretation of this simple analog is that a partitioning of the independent microscopic potential U results in two effects: 1) material dynamics (expansion) and 2) material structure (continuity). Therefore, analogous to adding a continuity constraint to the hydrodynamic action, the next section works out the consequences of adding a measurement constraint to the GR action.[8]

3. Measurement Condition Constraint and Quantization of Space

We now consider the Lagrangian density for the Einstein equations with only a cosmological constant term proportional to $\sqrt{-g} = e$ and an added observer measurement constraint[8] analogous to the continuity constraint of the previous section

$$\mathcal{L} = \frac{1}{2\kappa} e [R - 2(\Lambda + \Delta\Lambda)] + P_I^\alpha \left(\mathcal{D}_\alpha X^I - e_\alpha^I \right) \quad (4)$$

where $\kappa = 8\pi G$ ($c = 1$), e is the determinant of the tetrad field e_α^I (i.e. $g_{\alpha\beta} = e_\alpha^I e_\beta^I$), ω_α^{IJ} is the spin connection and the covariant derivative is defined as $\mathcal{D}_\alpha X^I = \partial_\alpha X^I + \omega_\alpha^{IJ} \eta_{JK} X^K$. Our convention[9] is that upper case Roman indices transform under local $SO(1,3)$ transformations and lower case Greek

¹ Of course $t = T$ in Eqs. (1-3), but derivatives with respect to t assume $\mathbf{x}$ is held constant and derivatives with respect to T assume $\mathbf{A}$ is held constant.

indices transform under general coordinate transformations with lower case Roman indices referring only to spatial components. Also repeated indices imply summation. Notice that the cosmological constant is partitioned into two contributions which will be identified according to their physical effects as determined by the value of P_I^α . As in Reference [8], the measurement condition $\partial_\alpha X^I = e_\alpha^I$ for observable spacetime is generated as a constraint from variations of Eq. (4) with respect to P_I^α . Variations of $\mathcal{L}$ with respect to e_α^I give

$$P_I^\alpha + \Delta\bar{\Lambda}e e_I^\alpha = -\frac{1}{\kappa}e \left(e_K^\alpha e_I^\gamma e_J^\beta R_{\gamma\beta}{}^{KJ} - \frac{1}{2}e R e_I^\alpha \right) - \bar{\Lambda}e e_I^\alpha \stackrel{?}{=} 0 \quad (5)$$

where $\Delta\bar{\Lambda} \equiv \Delta\Lambda/\kappa$, $\bar{\Lambda} \equiv \Lambda/\kappa$ and $\bar{\Lambda} + \Delta\bar{\Lambda}$ can be identified as the vacuum energy density ρ_0 for the matter fields.[10] While the partitioning of the cosmological constant in Eqs. (4&5) is generally arbitrary, here it is assumed to be chosen such that all sides of the equality are zero. Therefore the $\Delta\bar{\Lambda}$ only contributes to the Lagrange multiplier term and the $\bar{\Lambda}$ only contributes to the traditional form of the Einstein equations leading to a standard empty Lemaître cosmology of an expanding universe.[10] As noticed in Ref.[8], the solution to Eq. (5) seems underdetermined because nothing independently specifies P_I^α , but we will see that the choice of P_I^α does have physical consequences. This can be seen by taking the simplest case approaching a flat spacetime where both $\Lambda \approx 0$ and $R \approx 0$. Using this assumption with the first equality of Eq. (5), e_α^I can be eliminated from Eq. (4) according to

$$\mathcal{L} \approx 3 \left(\frac{1}{24\Delta\bar{\Lambda}} \epsilon_{\alpha\beta\gamma\mu} \epsilon^{IJKM} P_I^\alpha P_J^\beta P_K^\gamma P_M^\mu \right)^{\frac{1}{3}} + P_I^\alpha \left(\partial_\alpha X^I + \omega_\alpha^{IJ} \eta_{JK} X^K \right) \quad (6)$$

Working from the Eq. (6) approximation, we identify the conjugate momenta according to

$$\frac{\partial \mathcal{L}}{\partial(\partial_0 X^I)} = P_I^0 \equiv \Pi_I \quad (7)$$

which implies the quantum commutation relations

$$\frac{1}{i\hbar} \left[X^I(x), \Pi_J(x') \right]_{x^0=x'^0} = \delta_J^I \delta^3(x - x'). \quad (8)$$

The Hamiltonian is then identified through

$$\mathcal{L} = \Pi_I \left(\partial_0 X^I \right) - \mathcal{H}_{\text{tot}} \quad (9)$$

where

$$\mathcal{H}_{\text{tot}} = -3 \left(\frac{1}{6\Delta\bar{\Lambda}} \epsilon_{0\beta\gamma\mu} \epsilon^{IJKM} \Pi_I P_J^\beta P_K^\gamma P_M^\mu \right)^{\frac{1}{3}} - P_I^a \left(\partial_a X^I + \omega_a^{IJ} \eta_{JK} X^K \right) - \omega_0^{IJ} \eta_{JK} \Pi_I X^K. \quad (10)$$

It can be shown that by reintroducing the determinant e as an auxiliary field, the same Hamilton's equations and constraints can be obtained from

$$\mathcal{H}_{\text{tot}} = -2\Delta\bar{\Lambda}e - P_I^a \left(\frac{1}{6e^2} \frac{1}{\Delta\bar{\Lambda}^3} \epsilon_{0bga} \epsilon^{MJKI} \Pi_M P_J^b P_K^g + \partial_a X^I + \omega_a^{IJ} \eta_{JK} X^K \right) - \omega_0^{IJ} \eta_{JK} \Pi_I X^K \quad (11)$$

where, in current approximations, all results can assume $e \approx 1$. It is interesting to notice that the Hamiltonian constraints are related to generators of a local Poincaré group. Variations of $\mathcal{H}_{\text{tot}}$ with respect to P_I^a give expressions that can be interpreted as infinitesimal translation in observable spacetime

$$\frac{1}{2e^2} \frac{1}{\Delta\Lambda} \epsilon_{0bga} \epsilon^{MJKI} \Pi_M P_J^b P_K^g + \partial_a X^I + \omega_a^{IJ} \eta_{JK} X^K = 0 \quad (12)$$

in coordinates where $\omega_a^{IJ} = 0$ can always be chosen at the point of interest.[8] Consistent with Eq. (5) approaching a flat spacetime we can pick spatially normal coordinates such that

$$P_I^a = -\Delta\bar{\Lambda} e \delta_I^a \left(\frac{\partial X^I}{\partial x^a} \right)^{-1} \quad \text{no summation} \quad (13)$$

giving a spatially discretized (Δx^a) Eq. (12) according to

$$\frac{1}{2\Delta\bar{\Lambda}} \epsilon_{0bga} \epsilon^{MJKI} \mathcal{P}_M \frac{\delta_J^b}{\Delta_b X^I} \frac{\delta_K^g}{\Delta_g X^K} + \Delta_a X^I = 0 \quad (14)$$

where Δ_a is taken as a symmetric finite difference operator, e.g. for $a = 2$

$$\Delta_2 X^I = \frac{X_{j_1, j_2+1, j_3}^I - X_{j_1, j_2-1, j_3}^I}{2} . \quad (15)$$

The discretized conjugate momenta $\mathcal{P}_L$ are defined by the discretized form of Eq. (8) as

$$\frac{1}{i\hbar} \left[X_{j_1, j_2, j_3}^I, \mathcal{P}_{J, j'_1, j'_2, j'_3} \right] = \delta_J^I \delta_{j_1, j'_1} \delta_{j_2, j'_2} \delta_{j_3, j'_3} \equiv \delta_J^I \delta_{jj'}^3 , \quad (16)$$

and can be represented as $\mathcal{P}_{Jj} = -i\hbar \partial / \partial X_j^J$ where $\mathbf{j}$ is shorthand for the parameter spatial indices (j_1, j_2, j_3) . Note that the discretized scales in parameter space do not appear in Eq. (14) at a point where $\omega_a^{IJ} = 0$ is chosen, therefore we will see that another scale emerges to define the continuum limit. Notice that the Eq. (14) constraint ($M = 0$) contains a local Schrödinger-like operator for observable time

$$C_{0,j} \equiv -i\hbar \frac{\partial}{\partial X_j^0} + \Delta\bar{\Lambda} \left(\Delta_1 X^1 \right) \left(\Delta_2 X^2 \right) \left(\Delta_3 X^3 \right) = 0 \quad (17)$$

where time evolution seems to require an inherent energy content of space – in this case supplied by excess contribution to the cosmological constant. Also, the three generators of spatial translations ($M = m$) are

$$C_{m,j} \equiv i\hbar \frac{\partial}{\partial X_j^m} + \frac{\Delta\bar{\Lambda}}{2} \left(\Delta_b X^b \right) \left(\Delta_g X^g \right) \left(\Delta_a X^0 \right) \epsilon^{0bga} \epsilon_{0bgm} = 0 . \quad (18)$$

While the interpretation of the Eqs. (17&18) constraints is not surprising, taken together they imply a nontrivial result: Observable space is quantized. This is shown by using the constraints to define the operators

$$J_{m,j}^0 \equiv X_j^m C_{0,j} + X_j^0 C_{m,j} = 0 \quad (19)$$

which can easily be diagonalized by rewriting them according to

$$\begin{aligned} (X_j^0 \mathcal{P}_{m,j} - X_j^m \mathcal{P}_{0,j}) &= \frac{\Delta \bar{\Lambda}}{2} (\Delta_b X^b) (\Delta_g X^g) \\ &\times (X_j^m \Delta_a X^m + X_j^0 \Delta_a X^0) \epsilon^{0bga} \epsilon_{0bgm} . \end{aligned} \quad (20)$$

Changing to traditional Fock-space operators

$$\begin{aligned} X_j^I &= \sqrt{\frac{\hbar \omega}{2}} (a_{I,j}^\dagger + a_{I,j}) \\ \mathcal{P}_{I,j} &= i \sqrt{\frac{\hbar}{2\omega}} (a_{I,j}^\dagger - a_{I,j}) \end{aligned} \quad (21)$$

with unknown ω and

$$[a_{I,j}, a_{I,k}^\dagger] = i \hbar \delta_{j,k}^3 \delta_{I,I} \quad (22)$$

the left-hand-side of Eq. (20), e.g. for the $J_{1,j}^0$, becomes

$$\begin{aligned} i \hbar (a_{1,j}^\dagger a_{0,j} - a_{0,j}^\dagger a_{1,j}) &= \\ \Delta \bar{\Lambda} (\Delta_2 X^2) (\Delta_3 X^3) (X_j^1 \Delta_1 X^1 + X_j^0 \Delta_1 X^0) \end{aligned} \quad (23)$$

which can be diagonalized with the canonical transformation

$$a_{0,j} = \sqrt{\frac{1}{2}} (b_{0,j} + b_{1,j}) \text{ and } a_{1,j} = i \sqrt{\frac{1}{2}} (b_{0,j} - b_{1,j}) \quad (24)$$

to give

$$\begin{aligned} \hbar (b_{1,j}^\dagger b_{1,j} - b_{0,j}^\dagger b_{0,j}) &= \\ \Delta \bar{\Lambda} (\Delta_2 X^2) (\Delta_3 X^3) (X_j^1 \Delta_1 X^1 + X_j^0 \Delta_1 X^0) . \end{aligned} \quad (25)$$

With the familiar number operators giving nonnegative integers $n_{1,j}$ and $n_{0,j}$, Eq. (25) can now be written as

$$\begin{aligned} (\Delta_2 X^2) (\Delta_3 X^3) (X_j^1 \Delta_1 X^1 + c^2 X_j^0 \Delta_1 X^0) &= \\ l^4 (n_{1,j} - n_{0,j}) \end{aligned} \quad (26)$$

where $l^4 \equiv 8\pi G \hbar / \Delta \Lambda c^3$ (c is explicitly added to show dimensional consistency). Repeating this procedure [Eqs. (20-23)] for each $J_{m,j}^0$, a consistent solution using, at least locally, synchronous coordinates[11] $\Delta_m X^0 = 0$ is that space *really is discrete*

$$X_j^m = l(j_m - j_{m,0}) \text{ or } \Delta X^m \geq l \quad (27)$$

where $j_{m,0}$ is a constant origin index and the j_m index is now required to satisfy: $j_m - j_{m,0} = n_{m,j} - n_{0,j}$. The arbitrary scales Δx^a seem to have been replaced with l , so there is no obvious logic to reintroduce

Δx^a to take the continuum limit – although, $\hbar \rightarrow 0$ does recover the classical continuum limit. This appears to be consistent with discretized expressions for Eqs. (17-23) because they are independent of the parameter scale Δx^a . Therefore, in 3+1 dimensions it appears that l , instead of the Planck length, emerges as the minimum distance in observable space. Additionally, unlike the Planck length, the minimum spatial scale derived here seems to be realized for any spatial dimension – for the approximations considered, the spatial scale in $D + 1$ dimensions would be $l_D = (8\pi G\hbar/\Delta\Lambda c^3)^{\frac{1}{D+1}}$. It is interesting to note that the larger fraction of the predicted cosmological constant ($\Delta\Lambda$) is swept-under-the-rug, so to speak, because it is cancelled by a Lagrange multiplier field [Eq. (4)] that represents an inherent energy content (dark energy) of spacetime – even flat spacetime. Of course any observed structure to space deviating from continuous could indirectly reveal the value of that underlying larger fraction. We then suggest that it is a small residual portion (Λ) that is observed as the astrophysical value.

4. Discussion

This work indicates that the inclusion of a spacetime measurement constraint[8] in the GR action implies an inherent quantization of space in GR. Additionally, the small value for the observed cosmological constant could be understood as being a residual standard model generated dark energy left over from the cancellation of $\Delta\Lambda e e_I^\alpha$ and P_I^α where most of the theoretically expected $\Delta\Lambda$ enables the structure of space. Rather than the Planck length, the quantized spatial scale of that structure is $(8\pi G\hbar/\Delta\Lambda c^3)^{1/4}$ which also indicates that the continuum and classical theories emerge as the same limit. A nontrivial quantum theory seems to require an inherent energy content of space supplied by an excess cosmological constant $\Delta\Lambda$. The case of $\Delta\Lambda \rightarrow 0$ results in the trivial solution of all spatial points being separated by infinite “observable” distances. Therefore, a summary for GR that parallels the interpretation of the hydrodynamic analog is that a partitioning of standard model predicted vacuum energy results in two effects: 1) spatial dynamics (accelerated expansion from Λ) and 2) spatial structure (minimum observable length from $\Delta\Lambda$). This work is not intended to compete with the depth of other insights on the nature of space in a quantum theory of GR.[12,13] In fact, comparing with the eigenvalues of the area operator in loop quantum gravity,[13] a Barbero-Immirzi parameter of $\gamma = (c^3/16\pi G\hbar\Delta\Lambda)^{1/2}$ is predicted. The difference here is that we propose an explicit spatially quantized solution even for a flat metric in 3+1 dimensions as it relates to the cosmological constant problem which has not been previously considered.[6] Of course, given a $\Delta\Lambda$ of $10^{120} \times$ the observed fraction (Λ), l here becomes the same order of magnitude as the Planck length l_P . Given a *mid-range* standard model estimate for $\Delta\Lambda$ of $10^{65} \times$ the observed Λ , a minimum spatial distance is predicted to be $l \approx 10^{-21}$ m which could be relevant to interpreting the very sensitive observations at LIGO.[14] Finally, it should be noticed that nothing here answers the question of what physics determines the specific partitioning. Possibly that question is addressed by a more detailed model of inflationary cosmology[15] or ultimately by an anthropic principle. Work is in progress to understand if a more rigorous result (beyond a *hint*) can be obtained with the inclusion of the full dynamics of GR in 3+1 dimensions.

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