Article

Understanding Λ with the Aid of Biconformal Gravity

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Abstract

We use the framework of biconformal gravity [1, 2, 3, 4] to explore the possibility of explaining non-anthropically the tiny observed value of the cosmological constant Λ. We focus especially on the account of Λ in [1], where (i) a nonzero Λ is necessary for the very existence of a meaningful gravity theory such as general relativity (GR), and (ii) the field equations of GR are derivable from the biconformal gravity action.

Keywords: Cosmological constant, biconformal gravity, general relativity, vacuum energy sequestering.

1. Introduction

N. Dadhich has argued [5] that a nonzero cosmological constant (CC) is a necessary condition for the very existence of gravity – in particular, gravity as described by a geometric theory such as general relativity (GR). Dadhich's proposal suggests the following two questions. First, is it possible to construct a model of GR that realizes this idea? And second, if such a model can indeed be found, does it suggest any new perspectives on gravity and the CC that are worth exploring? In what follows, we answer both questions affirmatively. Regarding the first question, it turns out that there already exists a GR-related gravitational theory which models Dadhich's idea that gravity requires a nonzero CC. The theory in question is the biconformal gravity theory presented in [1]. (There is also important material on biconformal gravity in [2, 3, 4] and references therein, but only [1] provides an account of the CC's role and significance.) As for the second question, this theory contains "resources" that make possible a non-anthropic explanation of the CC's measured value. Our goal here is to present this explanation, in the hope of contributing both to an understanding of Λ and to an interest in biconformal gravity itself.

As for the issue of explaining Λ's measured value, the importance of explaining this puzzlingly small value in *some* way or other is emphasized in [6]. The account of Λ there uses vacuum energy sequestering (VES) to deal with the radiatively unstable vacuum energy of quantum matter fields [6, and references therein]. We too will use VES in what follows; it is necessary to use VES here, or something like it, because (a) the Weyl (local conformal) symmetry of biconformal gravity demands that the theory's stress-energy tensor T_{ab} be trace-free, so that it receives no contributions from vacuum energy, and (b) biconformal gravity theory cannot satisfy this demand, since the theory by itself has no way to address the problem of vacuum energy's radiative instability, a problem that spoils any attempt to ensure that T_{ab} is traceless.

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We focus on the biconformal gauge theory of gravity presented in [1, 2], a theory denoted hereafter as "BCGT" (following [7]); and we argue that a non-anthropic explanation of Λ's observed value is obtainable when BCGT and VES are combined in a suitable manner.

It should be noted that a non-anthropic account of Λ has recently been proposed, in which Λ is dynamically driven to 0^+ [8, 9]. Using probabilistic methods, this model has been supplemented with arguments to the effect that Λ's being close to zero is overwhelmingly likely [10, 11]. In contrast, we describe here a *non*-probabilistic process by which Λ acquires its value, a value which is inversely proportional to the spacetime four-volume of the universe soon after inflation ends – and hence, given the effect of inflation on the universe's volume, a value which is indeed very close to zero. The question of how likely it is for Λ to have the tiny value that we observe is thus reduced to the question of how typical our universe's period of early inflation is. By thus reducing two apparently separate questions to a single one, our account of Λ achieves a theoretical simplification or unification that makes it worth considering. Accordingly, our main goal in what follows is to articulate this non-anthropic and non-probabilistic alternative to [8-11]. Achieving this goal requires us to address the problem of vacuum energy's radiative instability; and we do this by using VES, as noted above – specifically, we use the manifestly local version of VES in [12].

One may ask what the relationship is here between BCGT and VES. In particular, one might wonder whether VES' presence makes BCGT superfluous, so that the latter can just be omitted altogether. Part of the answer to this is that using BCGT is crucial to the non-probabilistic explanation of Λ's value mentioned above, so that something important is lost by omitting BCGT. In addition, it is arguable that BCGT and VES are more closely related than they appear to be. This can be seen by considering an analogy with the case of supersymmetry. It has been claimed that high-energy supersymmetry survives to low energies in the gravity sector: namely, it survives as a structure – the "supergravity form" – which is stable against loop corrections [13]. And analogously, we suggest, the conformal symmetry of BCGT survives in the matter sector at low energies in the form of a traceless structure – namely, the trace-free Einstein equations – which is stable against radiative (loop) corrections, with this stability being ensured by VES. Thus, using VES *in the context of BCGT* yields evidence of conformal symmetry's survival at low energies in the matter sector; and this provides motivation for combining BCGT and VES in the manner proposed here. (This does not, of course, provide evidence for BCGT itself; but it does remove a possible objection to our proposal for combining BCGT and VES.)

Here is a summary of what follows. In section 2, we describe the relevant details of BCGT; we also say more about the relation between BCGT and VES, and about some other issues that merit attention. We do not provide a comprehensive discussion of BCGT here but focus only on those aspects of the theory that are relevant to Λ. Sections 3 and 4 give our account of the process by which Λ's value is determined. In section 5, we show that this process yields a CC whose value agrees with current cosmological measurements. And in section 6, we conclude with some brief remarks that link the process we describe with certain other general types of process.

2. Some Basic Features and Implications of Biconformal Gravity

The BCGT of [1, 2] is invariant under Weyl transformations (local dilatations) of the metric. This theory is obtained by a biconformal gauging of 4-dimensional Euclidean space, which involves taking the quotient of this space's conformal group by its homogeneous Weyl subgroup; this yields an 8-dimensional metric phase space composed of two 4D Lagrangian submanifolds, one of which is a configuration space and the other a momentum space. The configuration-space submanifold is necessarily Lorentzian and is equated with spacetime. The momentum-space submanifold may (but need not) be Euclidean; in addition, it may (but need not) be conformally flat. This 8D model of phase space includes a torsion one-form $\mathbf{T}^a$; when $\mathbf{T}^a$ is set to zero *and* the momentum space is taken to be flat, general relativity with local scale invariance is obtained on the tangent bundle of spacetime [2, 3]. Hence, since our interest here is in BCGT *as a model of GR* – an interest motivated by GR's obvious relevance to our universe – we assume here both zero torsion and a flat momentum space.

Now, the conformal symmetry of BCGT requires that the theory's stress-energy tensor T_{ab} be traceless; and given the claim in [1, sec. 7.2] that the trace $T^a{}_a$ of this tensor is *gauge dependent*, one might conclude that $T^a{}_a$ can indeed be removed or eliminated from the field equations of BCGT by suitably adjusting the SU(N) gauge [1, sec. 7.2]. However, the local trace anomaly of a tensor such as T_{ab} has in fact been shown to be gauge *independent* [14], and so $T^a{}_a$ here *cannot* be removed by the above gauge adjustment. More generally, quantum corrections to the vacuum energy spoil any attempt to eliminate the trace of the energy-momentum tensor in a theory with conformal symmetry [15, sec. 2.1] [16, sec. 4.3]. Thus, to ensure that the field equations of BCGT are trace-free, it is necessary to supplement BCGT with a mechanism that achieves a radiatively stable cancellation of vacuum energy – i.e., a cancellation unspoiled by quantum corrections.

One such cancellation mechanism is presented in the theory of vacuum energy sequestering, or VES [17, 16, 12, 6, 18, 19, 20]. The cancellation process in VES has a strongly global character, which leads to the replacement of certain local parameters by their global spacetime averages, where the averaging is over the entire cosmic history of the universe. Given the local character of spacetime gravity in BCGT, it is not clear that there is suitable initial motivation for combining BCGT and VES. We therefore begin by assuming the existence of a *purely local* mechanism for canceling vacuum energy, namely the mechanism described in [21]. When employed in conjunction with BCGT, however, this mechanism leads to a vanishing of BCGT's CC Λ, an effect which is highly problematic since Λ's vanishing threatens the very viability of a BCGT universe (as explained below).

To resolve this problem, we describe a hypothetical process by which a *new* nonzero CC emerges; and since, as it turns out, certain global considerations are an important part of this process, it is natural to view the new CC's emergence as accompanied by – indeed, as a key part of – a transition from [21]'s local cancellation mechanism to the global one of VES. Admittedly, the global character of VES is much more extensive than that associated with the new Λ's emergence; but the latter globality, by providing a kind of "lead-in" to VES, significantly strengthens the motivation for introducing VES here.

Because of the above-mentioned need for a nonzero CC in BCGT, the vanishing of the original Λ represents a failure or breakdown of the cosmic gravitational system, which has the potential to plunge the entire universe into chaos and uncertainty. Disaster is averted here, however, by the swift emergence of both a new Λ and a new mechanism for canceling vacuum energy. We regard the emergence of these two things here as exemplifying the general tendency of complex systems to undergo evolution at the edge of chaos (on this tendency, see [22] and references therein). Now, the process that gives rise to the new Λ here determines a specific nonzero value for this Λ, a value that agrees with the results of cosmological observations; and we will argue that causality considerations constrain this value to be *minimal*, which gives us an understanding of Λ's extremely small value.

Before describing the proposed process by which (the new) Λ emerges, we need to first say more about BCGT itself. The 8D biconformal manifold of BCGT has a single conformal curvature tensor with four distinct components: the torsion $\mathbf{T}^a$, the co-torsion $\mathbf{S}_a$, the curvature, and the dilatation [2, sec. 2.1]. (In [1, 2], lower-case Latin indices denote orthonormal frame fields that span either a biconformal manifold or any of its submanifolds, while lower-case Greek letters are used for coordinate indices.) Consider an 8D BCGT manifold M – a "biconformal space" – that has a 4D spacetime submanifold and a 4D momentum-space submanifold. If M's torsion and co-torsion are both zero, then it can be proven [2, sec. 3.4] that each of these submanifolds is completely flat – i.e., all four of M's curvature components vanish on the two submanifolds. (Note that a flat spacetime here lacks any sort of local gravity, such as that of GR.)

In such a case, it is still possible for M's curvature and dilatation to have nonzero (constant) *cross-terms*, so that the full biconformal space is *not* flat. Such a non-flat M with flat submanifolds is called "trivial;" and the Triviality Theorem of BCGT [2, sec. 3.4] is just the statement that, for an 8D biconformal space with nonzero curvature and dilatation cross-terms, "$\mathbf{T}^a = \mathbf{S}_a = 0$" is a sufficient condition for the space to be trivial. This theorem implies that, for an 8D BCGT manifold M such that M's 4D spacetime submanifold admits local gravity – and hence is not completely flat, so that M is non-trivial – M's torsion $\mathbf{T}^a$ and co-torsion $\mathbf{S}_a$ cannot both be zero. Since the BCGT of [1, 2] is assumed to be torsion-free (in accordance with GR), the above implication of the Triviality Theorem tells us that the existence of local spacetime gravity (and hence, the applicability of GR to spacetime) *requires* a nonzero $\mathbf{S}_a$.

Furthermore – and crucially, for our purposes – the BCGT of [1] is such that $\mathbf{S}_a$ is nonzero only if the CC Λ_0 is nonzero [1, sec. 6.2.7]; hence, a zero Λ_0 makes $\mathbf{S}_a$ zero, thereby entailing that spacetime lacks (local) gravity altogether. Λ_0 is essentially – *modulo* some constant numerical factors of order 1 – the CC of GR [1, sec. 6.2.7]. (It is important to note that [1] and [2] both contain a constant term Λ associated primarily with the curvature and dilatation components of the conformal curvature tensor. The Λ of [1] (see secs. 3.2 and 6.2.2 - 6.2.4 there) is clearly not a CC and should not be conflated with Λ_0. Unfortunately, [2] is less clear about *its* Λ term, which differs somewhat from the Λ of [1] (to see the difference, cf. [1, sec. 6.2.4] with [2, secs. 2.4, 3.3, 3.4]); the Λ of [2] *is* referred to as a cosmological constant at one point [2, sec. 3.4], but the use of scare quotes there leaves it unclear how strict or literal this characterization of Λ is intended to be. In any case, the Λ of [2] is emphatically *not* the CC Λ_0 of [1]; and our concern here is with [1]'s Λ_0 alone, and with the implications of *its* being zero.)

The above relation between $\mathbf{S}_a$ and Λ_0 is clear from the following equation, which is obtained by identifying the tensor field c_{ab} of BCGT with $\Lambda_0\eta_{ab}$ [1, sec. 6.2.7]:

$$\mathbf{S}_a = 2(1+\chi)\,\Delta^{bc}_{ea}\,y_b\Lambda_0\eta_{cd}\mathbf{e}^d \wedge \mathbf{e}^e. \tag{1}$$

Regarding this equation, note the following points: (i) χ is a specific constant [1, sec. 6.2.4], such that $1+\chi$ may be canceled by "generic constants in the action" [2, sec. 3.3]; (ii) $\mathbf{e}^d$ and $\mathbf{e}^e$ are solder forms that serve as orthonormal frame fields, each of which spans a submanifold of the full (8D) biconformal space; (iii) η_{cd} is the metric of Minkowski spacetime with orthonormal basis; and (iv) y_b is a canonical momentum-space coordinate [2, secs. 1.2.1, 6.2], with the antisymmetric projection operator Δ^{bc}_{ea} [23, sec. 2.2] acting on $y_b\mathbf{e}^d$ in such a way that the 4D spacetime Minkowski metric is obtained from the full biconformal space spanned by $\mathbf{e}^d \wedge \mathbf{e}^e$. (Note that "$1+\chi$" in eq. (1) cannot equal zero, since eq. (101) of [1] – which is a crucial equation regarding the co-torsion – contains fractional terms having "$1+\chi$" in their *denominators*.) A final point to note is that c_{ab}, or $\Lambda_0\eta_{ab}$, can be viewed as the field strength tensor of the co-solder form $\mathbf{f}_a$ (i.e., the gauge field of special conformal transformations [2, sec. 2.1]).

We thus see that if Λ_0 were to vanish, then according to the BCGT of [1] the co-torsion $\mathbf{S}_a$ would vanish as well, making the biconformal space trivial and thereby entailing the disappearance of the spacetime universe's gravity (i.e., the gravity that GR describes). Such a disappearance of gravity, being tantamount to the vanishing of the stress-energy tensor T_{ab} – the very source of gravity here – would represent an enormous violation of the First Law of thermodynamics, which mandates that energy be conserved. To avoid such a violation, while attempting to satisfy the requirement or demand that gravity be absent, it would be necessary to change the universe's entire past, so that gravity would be absent *ab initio*. Such a change is of course impossible; but the point here is that the vanishing of Λ_0 nonetheless gives rise to a *demand* that gravity be absent, and – given the First Law – both the present *and* the past of the (4D) spacetime submanifold are subjected to this demand. And even though this demand itself cannot be satisfied, it still has an effect, or makes a difference: specifically, it disturbs, or puts "pressure" on, the entire spacetime four-volume existing at the time of Λ_0's vanishing, thereby causing perturbations *everywhere* on this four-volume.

As explained below, these perturbations represent the beginning of a process which – together with certain other factors – leads to the creation of a *new* nonzero CC, thus putting an end to the demand that gravity disappear. Before we consider this process, however, it is necessary to explain why and how Λ_0 might be expected to vanish in the first place, a vanishing which gives rise to the conditions that lead to the new CC's emergence, conditions which give this CC a numerical value in agreement with current measurements.

3. Why Λ_0 Gets Canceled in Bcgt, and the Consequences of This Cancellation

As noted earlier, it is necessary in BCGT that there be some way of ensuring in general that the vacuum energy of quantum fields does not contribute to the stress-energy tensor of matter (though there may be some exceptions, most notably the case of inflation – on which see below). The sensitivity of ρ_{vac} to UV corrections and phase transitions provides additional motivation for a mechanism that can cancel or nullify this cosmological vacuum energy once the universe's inflationary period has come to an end. Since BCGT is a local theory, it seems reasonable to use a local cancellation mechanism in connection with it.

And it so happens that an effective cancellation mechanism of the desired type has indeed been proposed [21], which uses a conformal coupling $A(\varphi)$ between the Einstein and Jordan frames, where φ is a scalar field, to couple a second scalar field λ to the trace $T^a{}_a$ of T_{ab}. The field φ then acts as a Lagrange multiplier that constrains λ to cancel the vacuum energy density ρ_{vac}. This mechanism drives ρ_{vac} to zero in an efficient manner, achieving this goal as the radiation-dominated era is just beginning, which – assuming instant preheating [24], as we do here – corresponds approximately to the end of cosmic inflation.

Regarding the question of why the cancellation mechanism here does not prevent the occurrence of inflation itself, one answer is that this mechanism represents a low-energy effective model "that only applies after the inflation era" [21, sec. VI.A]; there are other, more complicated possibilities too [21, sec. VI], but for simplicity we will adopt the above-mentioned answer here. (As an aside, we point out that the account of Λ presented here does not depend on or require the assumption of instant preheating; this assumption is made here mainly for specificity. The same basic account of Λ can still be obtained using different assumptions about, e.g., the duration of (p)reheating, though there is of course some limit on what is allowable; trying to consider a range of different assumptions here, however, would make the present discussion overly complicated.)

The above cancellation mechanism has an important limitation, however. As noted in [21], nonrelativistic matter in the early universe may have equations of state that are quite complicated; hence, during the matter-dominated era, there is no simple and unambiguous way to distinguish between some of the *matter-sector* contributions to the universe's total energy density, on the one hand, and the contribution that ρ_{vac} makes to this energy density, on the other hand. As a result, λ's coupling to $T^a{}_a$ "also generates a nondesired coupling [of λ] to the density of nonrelativistic matter" [21, sec. I], so that the latter energy is canceled along with that of the vacuum. This excess cancellation is a problem because it leads to insufficient structure formation in the early universe (some tentative efforts to address this problem are made in [21]).

Our concern here, however, is with another nondesired coupling that can be expected to occur when the cancellation mechanism of [21] is applied to *BCGT* – with its occurrence being expected there for the same reason that the authors of [21] expect *their* nondesired coupling to occur. Specifically, the scalar field λ's coupling to $T^a{}_a$ can be expected to generate a nondesired coupling of λ to the trace $c^a{}_a$ of the field strength tensor $c_{ab} = \Lambda_0\eta_{ab}$ (where Λ_0 is the CC), a coupling that causes λ to cancel Λ_0's energy density, so that Λ_0 vanishes. This nondesired coupling is clearly unavoidable, since c_{ab} has the form of – and thus effectively *is* – a stress-energy tensor of the vacuum, so that (a) c_{ab} is formally or qualitatively *indistinguishable* from T_{ab}'s vacuum sector $T^{\Lambda}{}_{ab}$, and (b) c_{ab}'s trace $c^a{}_a$ is likewise indistinguishable from $T^a{}_a$. (The formal identity of c_{ab} and $T^{\Lambda}{}_{ab}$ reflects the fact that in local inertial coordinates, both c_{ab} and $T^{\Lambda}{}_{ab}$ are proportional to the Minkowski metric η_{ab} [1, sec. 6.2.7] [25, p. 12].) Since Λ_0 thus goes to zero, the co-torsion $\mathbf{S}_a$ vanishes as well (see eq. (1)), which in turn – by the Triviality Theorem of BCGT – mandates the disappearance of gravity itself.

As will be seen, the problematic character of this mandate triggers a process that leads to the emergence of a new CC, which is *protected* from cancellation as the result of a transition from the cancellation mechanism of [21] to the mechanism of vacuum energy sequestering (VES). Now, the fact that the mechanism of [21] thus disappears from the scene almost as soon as it becomes effective may seem rather odd and puzzling – especially since all that this mechanism manages to "accomplish" is the seemingly accidental and unwanted elimination of the universe's original CC. Would it not be simpler to just begin with VES? Any attempt to answer this question is necessarily speculative; but we may note here that the emergence of a new value for the CC *after* inflation has ended, at a time when information about the effect of inflation on various important cosmological parameters is available, makes it possible for the process that gives rise to a new CC here to utilize this information in the course of determining this CC's value. In particular, using the information in question may help ensure that the new CC is not so large that it prevents structure formation in the developing universe.

How, and whether, the universe "knows" to use this information to facilitate structure formation is a question on which we will not speculate here. But the preceding remarks at least suggest the possibility that the quick disappearance of the original mechanism for canceling vacuum energy has a positive rationale after all: namely, it makes possible the emergence of a new CC with a numerical value "informed" by cosmological data in such a way that it allows ample opportunity for structure formation. And since it is the cancellation of the original CC by the mechanism of [21] that initiates the process which gives us the new CC, this mechanism is clearly of great importance despite its extremely short lifespan. (One might object that the new CC-value may, for all we know, be of the same order as the original value, in which case there would be no need for the cancellation mechanism of [21].

However, since the range of possible CC-values is very large indeed – or so our current knowledge strongly suggests – the chances of the original and new CC-values being approximately equal are extremely remote.) It should also be noted – as will be shown later – that the process of the new CC's determination is such as to favor structure formation not only in our universe, but in universes that differ from ours with respect to the number of inflationary e-folds. Thus, a universe with more e-folds of inflation than ours, and which is therefore more "diluted" when inflation ends, will have a proportionally smaller CC than our universe by virtue of the very process which, on the present account, determines the (new) CC's value; this smaller CC decreases the rate of further dilution relative to our universe, thereby aiding structure formation in the other universe. On the other hand, a universe with fewer e-folds of inflation than ours will have a relatively large CC – again, by the very nature of the way the CC's value is determined here – and such a CC, by helping to prevent the gravitational collapse of its universe, enhances the prospects for structure formation there.

In what follows, we suppose that Λ_0 vanishes at the end of (p)reheating due to the cancellation mechanism of [21], with this mechanism becoming effective when inflation ends. As a result, the universe at the end of (p)reheating is on the verge of chaos, due to the "cosmic uncertainty" that Λ_0's vanishing causes. We propose that this uncertainty itself initiates a process that gives rise to a new nonzero Λ, a process that represents a kind of cosmic self-healing; and we show that, given reasonable assumptions, this new Λ has a numerical value that matches the observed value.

Obviously, such an approach requires adding extra ideas to the BCGT of [1]. The result, however, is to vindicate [1]'s BCGT framework itself by showing that this framework helps make possible an explanation and understanding of the CC's observed value. In particular, using BCGT enables us to explain why this value is so close to zero, thereby resolving "one of the most puzzling open problems in theoretical physics" [26, abstract].

4. More on the Implications of Λ_0's Vanishing

In BCGT, as noted, a vanishing CC entails the disappearance of gravity. But gravity's disappearance means that T_{ab} must vanish as well; and T_{ab}'s vanishing, in turn, would represent a severe violation of the First Law of Thermodynamics, which prohibits energy from simply disappearing. Thus, we seem to have an impasse here, due to the conflicting demands of different physical laws, or principles – namely, the BCGT-rooted demand for T_{ab}'s disappearance, on the one hand, and the thermodynamics-based prohibition of any such vanishing of T_{ab}, on the other hand. This impasse occurs at the cosmic time t_{preh} that corresponds to the end of preheating – since that is when the CC vanishes, which triggers the impasse – and it puts the spacetime manifold in the impossible situation of having to comply with a set of *mutually irreconcilable* demands. On the one hand, this manifold is required to become flat, which means that T_{ab} must vanish; while on the other hand, T_{ab}'s vanishing is forbidden, so that spacetime is subject to the demand that it *not* become flat.

The impasse that these irreconcilable demands create affects time itself; in particular, it makes it impossible for any times t such that $t > t_{preh}$ to be marked by events and states that are *causal consequences* of the situation at t_{preh}. In other words, causal sequences of events are obstructed or interrupted at t_{preh}. Perturbations of various fields may still occur; but given the impasse here, any "causal flow" from t_{preh} to later times is obstructed. Thus, although the passage of time here may be marked by perturbations, there is an absence of temporal causal evolution. Also, as explained later, the uncertainty that the impasse induces – i.e., uncertainty about whether the spacetime manifold as a whole is to become flat or not – is present not only at t_{preh} itself; it pervades all times t such that $t < t_{preh}$ as well. As a result, perturbations affect the entire spacetime four-volume extending from $t = 0$ to $t = t_{preh}$. Thus, insofar as the "flow of time" consists of perturbations, we have a situation in which there is no single or unique locus of time-flow; in other words, the flow of time – and hence time itself – is effectively delocalized.

Because of the above impasse, the spacetime manifold does *not* – indeed, is *unable to* – become completely flat when the CC vanishes. Yet since the CC's vanishing, in BCGT, *entails* or *requires* spacetime flatness, this failure of spacetime to become flat creates an additional element of uncertainty as to whether Λ_0 has really vanished after all. Without actual evidence of a nonzero Λ_0, however, this uncertainty might seem too nebulous to produce any definite effects. Suppose, however, that this uncertainty couples to the impasse-induced perturbations of the spacetime manifold, thereby acquiring a certain energy of its own. And suppose further that, at the boundary between the spacetime and momentum submanifolds, spacetime transmits some of this perturbative "uncertainty-energy" to momentum space – a transmission which represents a "distress signal" that perturbs the momentum submanifold and thus endows this manifold itself with some (limited) dynamics.

Now admittedly, the BCGT of [1, 2] constrains momentum space to be flat and non-dynamical [3] [7, sec. III.D]; but the urgent need for an effective response to the extraordinary and problematic impasse here may lead to some relaxing of this constraint in the present case, perhaps via a noncommutative deformation or "fuzzifying" of the geometry in a localized region of momentum space. Nonetheless, the fact that momentum-space flatness is an important constraint suggests that the extent of this deformation should be *minimal* – specifically, the deformation should be confined to a region of minimum size, where the "minimum" is set by a physical minimal-length scale that is close to the Planck scale (on the existence of such a scale, see [27, 28, and references therein]). The perturbative energy E that spacetime imparts to momentum space would then be confined to this Planck-sized region P.

Since the fuzzy point P and its energy E are supposed to reflect or express *uncertainty* about Λ_0's numerical value, we may think of them as "hiding" or "obscuring" information about what this value actually is. (On this view, P is effectively a minimal "field space of Λ-values" that includes a geometrical (i.e., non-fuzzy) point corresponding to "$\Lambda_0 = 0$," along with any other CC-values that are (approximately) a Planckian field-space distance away from "$\Lambda_0 = 0$.") This suggests treating P as a (Planckian, noncommutative) *black hole*, of the sort described in [29] (and having a singularity at $\Lambda_0 = 0$). The noncommutative black holes of [29] have a de Sitter line element, and thus they are filled with a positive, repulsive energy – vacuum energy, effectively – that can be viewed as repelling any attempt to probe or measure Λ_0's value, thus enabling this value to remain uncertain. As a result, we may take E itself to be of Planckian order.

Also, we treat P as effectively part of the boundary between spacetime and momentum space; we may think of P here as a sort of "hybrid" of momentum space and this boundary, such that P belongs to *both*. To put it more fully, P "deforms" momentum space, in part, by becoming the locus of an "intersection" or intertwining between momentum space and its boundary with spacetime; and this in turn makes possible an intertwining between P and spacetime itself (cf. the intertwining described in [30]), such that P couples to the spacetime tensor field c_{ab}. This coupling enables P's repulsive Planckian energy to be transmitted to the spacetime manifold, with this energy representing a response by momentum space to spacetime's impasse-induced perturbed state (a state which is effectively a "distress signal" that spacetime sends to momentum space).

This response is the first step of a process that culminates in the emergence of a new nonzero CC which, by its very existence, puts an end to the impasse here and thus allows spacetime to "return to normal." To understand how P's energy E can lead to such a result, it is necessary to consider the effects, both direct and indirect, that the impasse itself has on spacetime, since these play a crucial role in enabling E to contribute to the new CC's emergence.

As noted, the impasse gives rise to uncertainty regarding whether Λ_0 is in fact equal to zero (at $t = t_{preh}$). Now, consider a spatial slicing of the 4D spacetime manifold into hypersurfaces $\Sigma(t)$, and focus on $\Sigma(t_{preh})$. The above uncertainty is clearly *global*, in the sense that it is a condition or state of the entire hypersurface $\Sigma(t_{preh})$. Recall now that the energy E is momentum space's way of expressing this uncertainty in a quantitative form; and so, when E is transmitted to the spacetime manifold, its manifestation there must be global as well, just like the uncertainty that it models or expresses. In other words, E needs to be *spatially delocalized* over the entire $\Sigma(t_{preh})$. Hence, E's coupling to c_{ab} must be a nonlocal coupling that effectively disperses E, in a uniform manner, to every location on $\Sigma(t_{preh})$. (For a different use of nonlocal couplings in connection with the CC, see [31].)

Admittedly, delocalization is generally regarded as a *quantum* effect, which might lead one to question the legitimacy of invoking delocalization here, in a context that is macroscopic and hence non-quantum. In response, we note that the impasse discussed here, though not a quantum phenomenon, has a *stochastic* character, due to the fact that a conflict between different physical laws or principles – such as the conflict that is the source of the impasse here – is *not* a law-governed process with a predictable outcome. Instead, it is something chaotic and unpredictable that may generate novel, unanticipated phenomena and results. And, crucially, there is a significant correspondence and overlap between processes describable in stochastic-mechanical terms and processes that admit a quantum-mechanical description [32, and references therein]. As a result, the occurrence of quantum-like delocalization here can be understood in terms of a stochasticity which leads to effects similar to those produced by the factors that make quantum systems delocalized.

Not only is the energy E delocalized *spatially* in the above-described manner; E is also delocalized *temporally*, since time itself becomes delocalized here. To describe and explain this temporal delocalization, we begin by asking what it means to say that a quantum particle is spatially delocalized; and our answer is as follows: a quantum particle confined to a spatial region R is (spatially) delocalized in R iff, for any given point x in R, the particle's probability pr(x) of being at x is such that, for every other point y in R, pr(x) = pr(y). This statement has two important implications. First, there is *no* point or location in R where the delocalized particle *actually is*; for if there were such a point x, then we would have both (a) pr(x) = 1, and (b) pr(y) = 0 for every other point y in R, which contradicts the requirement that pr(x) = pr(y). Thus, a delocalized particle has no actual location; we can only speak of where such a particle potentially *could* or *might* be, and not of where it actually *is*. Second, every point in R is *equally* the (potential) location of the delocalized particle; in other words, each point in R has an "equal claim" to be the particle's location, so that the particle's amplitude is effectively "*smeared" uniformly* over R.

Turning now to the case of time and its delocalization (for a different treatment of delocalized time, see [33]), we note that the existence of time – i.e., its existence as something actual and not merely potential – is tantamount to there being a *passage* or *flow* of time. This view is not often stated explicitly; instead, it usually has the character of an implicit assumption (as in [34], e.g.). Although there is nothing wrong with this, we find it important to state this view explicitly here because the impasse we are dealing with is such that it obstructs the flow of time itself, thereby calling into question time's very existence. The presence of such an obstruction leads us to characterize time's delocalization in a manner that parallels the above account of a particle's spatial delocalization. Thus, and analogously to our focus on a *spatial region* R in which such a particle is delocalized, we consider here a *spacetime manifold* M in which each spatial and temporal dimension has a certain finite length. We let M be four-dimensional, and we assume a spatial slicing of M into hypersurfaces Σ(t); M may thus be viewed as the manifold of a physical universe like our own, which grows and evolves over time. We focus exclusively on one particular time interval in M's history, an interval which – and here we assume that M's evolves in a manner similar to our own universe – extends from an initial time t = 0 up to and including the time $t = t_{preh}$ at which (post-inflationary) preheating ends.

We can now express the idea of time's delocalization, using two main points. First, to say that time is delocalized is to say that there is no "place" – i.e., no temporal location, or no "point in time" – where time flows or passes. This clearly implies, given what was said above about time's existence, that delocalized time does not exist as something "actual;" it only exists as something that has the "potential" or "capability" of *becoming* actual time. And second, every temporal location in M – extending from t = 0 up to and including $t = t_{preh}$ – is *equally* the (potential) location of time, or has an "equal claim" to *become* the actual time (i.e., to become the locus of a "renewed" flow or passage of time). And so, due to the impasse-induced obstruction of time's flow at $t = t_{preh}$, we propose that (a) time becomes delocalized there, and (b) the energy E from momentum space is therefore delocalized temporally as well as spatially. This means that E's nonlocal coupling to c_{ab} is such that E is *dispersed uniformly* over the entire spacetime four-volume $\mathcal{V}$ consisting of both the spatial three-slice $\Sigma(t_{preh})$ and all spatial three-slices to the past of it. ($\mathcal{V}$ itself may be regarded as the volume of the past light cone of a representative point on $\Sigma(t_{preh})$.)

On extremely small timescales, the above uniformly dispersed energy E has the form of an actual CC; and we therefore suggest that this dispersed energy *mimics* a CC on such timescales, thereby putting a temporary end to the impasse and its obstruction of time. This provides a brief window of time in which a new CC can emerge as part of a cosmological phase transition – an instance of evolution "at the edge of chaos" – thus making the impasse's disappearance *permanent* (assuming that the new CC is radiatively stable and not subject to cancellation).

We also propose that the dispersed energy E acts as *information* which provides an effective "CC-template" capable of determining or fixing a suitable numerical value for the new CC. By a "suitable" value, we mean one which is (a) sufficiently small to ensure that the universe's expansion is not so rapid that it inhibits the formation of cosmic structure, and (b) large enough to eventually produce an accelerated cosmic expansion, something that is arguably necessary from a thermodynamical standpoint [35].

The above-mentioned cosmological phase transition that E's mimicking of a CC makes possible is a transition from the vacuum energy cancellation mechanism of [21] to the alternative cancellation mechanism associated with vacuum energy sequestering (VES). It is reasonable to expect that the impasse here greatly perturbs the universe, thereby facilitating novel effects and processes that can trigger such a phase transition. For example, fields from a non-gravitating topological sector may interact with the gravitational sector in such a way as to lead to (a) the QFT vacuum energy being sequestered in this topological sector, and (b) the emergence of a residual CC "$\Delta\Lambda$," which is independent of QFT and not subject to radiative corrections, and which may thus be equated with the observed CC of our universe. (The motivation for such a topological sector can come from (e.g.) flux-monodromy models of inflation; for recent accounts of such models, see [6, 18, 36] and references therein.) The transition to VES here is also aided by the fact that two scalar fields that are crucial to the ρ_{vac}-cancellation mechanism of [21] – namely, the fields λ and φ mentioned earlier – have roles that largely resemble the roles played by certain scalar fields in VES.

This similarity, we suggest, enables λ and φ to be "repurposed" for use in VES, thereby helping to facilitate the transition process here. More specifically, we may view the vacuum-energy-canceling scalar field λ of [21] as being transformed into the scalar field **Λ** of VES, which is similarly responsible for canceling this same vacuum energy. (Boldface type is used here to distinguish this VES field from the CC itself.) And the coupling field φ, which in [21] performs conformal re-scalings between the Einstein and Jordan frames, can likewise be viewed as transforming into the scalar field κ of VES, which allows us to go from Einstein-frame to Jordan-frame variables [12].

We take these new fields **Λ** and κ to couple to c_{ab}, a coupling that reflects (a) their close connection to the (new) effective CC $\Delta\Lambda$ of VES ($\Delta\Lambda$ is actually a *part* of **Λ**, as noted below), and (b) the fact that, in BCGT, c_{ab} is just $\Lambda_0\eta_{ab}$ and hence is inseparable from the effective CC, so that it *must* couple to the "new Λ_0" here. namely the emergent $\Delta\Lambda$ of VES. It is important to emphasize that c_{ab} does not vanish when Λ_0 is canceled; the remnant uncertainty about whether Λ_0 is actually zero (i.e., the same uncertainty that induces the energy E at the point P on the boundary between momentum space and spacetime) "sustains" c_{ab} until it couples to E. As noted earlier, this coupling leads to E's dispersal over the spacetime four-volume $\mathcal{V}$; but in addition, we propose, this coupling makes c_{ab} itself the "carrier" or "bearer" of *information* regarding the dispersed energy E – specifically, information about E's density ρ_E. And so, as indicated below, c_{ab}'s coupling to $\Delta\Lambda$ enables this information about ρ_E to act as a "template" that determines the value of $\Delta\Lambda$ itself.

Now – and here we use the accounts of VES in [12] and [37] – the new field **Λ** not only cancels the vacuum energy of quantum fields; it also contains, as a separate component, the residual CC $\Delta\Lambda$. The fields **Λ** and κ are held rigid *on-shell* by, respectively, the four-form fluxes F_4 and $\hat{F}_4$ from the topological sector, which couple to **Λ** and κ; the gauge symmetries of these fluxes remove local degrees of freedom from the latter fields. However, the *off-shell* behavior of **Λ** and κ determines a new effective CC, namely $\Delta\Lambda$ [12, eq. (9)], whose value is given by the flux ratio $\int\hat{F}_4 \big/ \int F_4$, where F_4 is a volume measure and the integration ls over the entire cosmic history of the universe. (The equation for $\Delta\Lambda$ includes not only this flux ratio but also some constant terms that can be ignored because they either get canceled or may be taken as O(1); to see the cancellation here, apply eqs. (4.30) and (4.31) of [38] to the second eq. (9) of [12].)

In the theory of VES, the above fluxes represent boundary data [19, 18], with $\Delta\Lambda$'s value being the result of some unknown extrinsic process [19]. This leaves it unclear, however, why $\Delta\Lambda$'s value is as small as it is, a question that is important because this smallness of $\Delta\Lambda$ does not seem to satisfy any criteria of "naturalness" [6]. This has led to the suggestion that $\Delta\Lambda$'s value should be explained anthropically [6].

Our proposed alternative to this suggestion begins with the idea that the above ratio of fluxes can be adjusted, or "tuned" [6, sec. 2], an idea which leads to our key hypothesis: namely, c_{ab}'s information regarding the dispersed energy E and its density ρ_E acts as a *template* which tunes or guides the flux ratio so that this ratio determines an energy density $\rho_{\mathbf{\Lambda}}$ for $\Delta\Lambda$ such that $\rho_{\mathbf{\Lambda}} = \rho_E$. Furthermore, this "information template" constrains the fluxes and their ratio on the whole boundary of spacetime, a constraint expressed by the fact that the fluxes are represented by *historic integrals* in the field equations (on such "non-standard" boundary conditions as a distinctive feature of VES, see [19]). We thus obtain an emergent (positive) CC $\Delta\Lambda$, with $\Delta\Lambda\eta_{ab} = c_{ab}$, which by its very existence brings the impasse to an end. Also, as noted earlier, the above determination of $\Delta\Lambda$'s value is not only non-anthropic; it is non-probabilistic as well.

The CC-template thus dictates what are effectively "new initial conditions" for the CC of BCGT; these initial conditions may be called "post-determined" (in the spirit of [39]), and they replace the initial conditions associated with the original Λ_0 – which *need* to be replaced due to Λ_0's vanishing at t_{preh}. The template's energy E, however, does more than simply dictate initial conditions on the spatial three-slice at t_{preh}; for as indicated, much of E is dispersed over the *past* light cone of a (typical) point on this three-slice. This dispersal raises the danger of a causality-violating alteration of the past. We suggest, however, that the dispersed energy here, rather than changing the past, simply acts as information that heralds $\Delta\Lambda$'s emergence and the consequent ending of the impasse. Such information needs to be provided to the past because, as noted earlier, the past itself is affected by the impasse that occurs at t_{preh} (this reflects the truly global ramifications of this impasse). Thus, the new information which the template provides, far from changing the past, simply lets the past know that it can remain *un*changed.

Since our focus is on the emergent residual CC $\Delta\Lambda$ and the determination of its value, we have not attempted to give a general account of VES here. Nor have we mentioned the use of VES to cancel vacuum contributions either from graviton loops [40], or from virtual axions that come into play when monodromies are used [41]. It should be noted that in both [40] and [41], the expressions for the effective CC $\Delta\Lambda$ become more complicated. Despite this, however, $\Delta\Lambda$'s value is still controlled or constrained by the same flux ratio which, on the account given here, is tuned by the CC-template to yield an energy density $\rho_{\mathbf{\Lambda}}$ for $\Delta\Lambda$ such that $\rho_{\mathbf{\Lambda}} = \rho_E$ (see [40] and [41, sec. 4]). So, the relatively complicated nature of the above-mentioned expressions for $\Delta\Lambda$ does not affect the account here of how $\Delta\Lambda$'s value is determined.

There is one further issue that should be addressed here regarding VES. Namely, one may wonder why VES' cancellation mechanism does not lead to a "nondesired coupling" of this mechanism to the new CC $\Delta\Lambda$, leading to a problematic cancellation of the latter in a manner analogous to the situation that we described earlier in connection with the mechanism of [19]. The answer, basically, is that the VES cancellation field and $\Delta\Lambda$ are both components of the scalar field $\mathbf{\Lambda}$, which as noted is made rigid by the flux fields. And this very rigidity prevents the cancellation mechanism from developing any new behavior that could cause $\Delta\Lambda$ itself to be canceled here.

We now summarize the main results of this section. First, recall that the spacetime four-volume $\mathcal{V}$ is the total volume of the spatial three-slice $\Sigma(t_{preh})$ *and* all spatial three-slices to the past of $\Sigma(t_{preh})$, where t_{preh} is the cosmic time, or proper time, at which preheating ends. (For "instant preheating" scenarios such as the one considered here (see section 5, below), t_{preh} is roughly the time at which inflation ends.) Now, consider the 4D spacetime submanifold M whose four-volume is $\mathcal{V}$. Integrating ρ_E over M gives us the following equation (where "E_{PL}" is the Planck energy):

$$\int_M d^4x\sqrt{-g}\ \rho_E = E = E_{PL}. \tag{2}$$

Combining this with $\rho_\Lambda = \rho_E$, we have:

$$\rho_\Lambda = \frac{E}{\mathcal{V}}\ . \tag{3}$$

And using Planck units (c=ℏ=8πG=1), we may then write:

$$\rho_\Lambda = \frac{1}{\mathcal{V}} = \Delta\Lambda. \tag{4}$$

Thus, ρ_Λ, $\frac{1}{\mathcal{V}}$ and $\Delta\Lambda$ are all equal in magnitude when (dimensionless) Planck units are used. As a result, and using the range of allowed values of $\mathcal{V}$ – where "allowed" means "in accordance with current cosmological models and data" – we can ask whether there is in fact a value of $\mathcal{V}$ within this range such that $1/\mathcal{V}$ equals the measured value of $\Delta\Lambda$. This is the task undertaken in the next section. Success in finding such a $\mathcal{V}$-value would show that our account of $\Delta\Lambda$ can explain the current accelerated expansion of the universe.

5. Explaining Λ's Observed Value

What remains to be done, then – if we are to achieve our goal of explaining the new CC $\Delta\Lambda$'s observed value – is to estimate the size of the above-mentioned spacetime four-volume $\mathcal{V}$; the relevant input here is provided by current estimates of various inflationary parameters, which we combine with a suitable type of model describing the (p)reheating that occurs when inflation ends. Specifically, we focus here on models of *instant preheating*, such that the time t_{preh} when (p)reheating ends – and hence, the time at which the primordial Λ_0 is expected to vanish due to cancellation – is very close to, and may even coincide with, the time t at which inflation ends, so that $t \sim t_{preh}$. (For representative examples of this class of models, see [24, 42]; this class also includes models of warm inflation, in which (p)reheating occurs during inflation itself [43]. The model in [24] is noteworthy for its close match with the latest cosmological observations.)

We begin by noting that Planck 2018 results [44] provide strong support for a high number of inflationary e-foldings [45]. Now, we do not know how large the universe was when inflation began, but we do have a range of values for the size of the universe when inflation ended [46]. It therefore seems reasonable, *given our ignorance of the universe's pre-inflation size*, to consider a universe whose size when inflation ends, or "post-inflation" size – and taking the universe's spatial radius r as the relevant size parameter here – is somewhat larger than the minimum allowed size, while still respecting upper bounds on r. We also assume that inflation ends at $t \sim t_{preh} \sim 10^{-32}$ s, which is a commonly used value.

The question we are faced with, then, is this: given $\Delta\Lambda$'s measured value, together with eq. (4) (in which Planck units are used), can the post-inflation spacetime four-volume $\mathcal{V}$ be reasonably estimated to have a value that satisfies "$\Delta\Lambda = \frac{1}{\mathcal{V}}$"? If so, then our proposed explanation of $\Delta\Lambda$'s size will have passed an important test of its viability.

To address this question, we begin by specifying the particular value of $\Delta\Lambda$ to be used here, a value in agreement with recent observations. By taking H_0 = 69.8 km/s/Mpc [47] and $\Omega_{\Lambda 0} = 0.70$ [48] – each of these values lying roughly in the middle of the current allowed range for H_0 and $\Omega_{\Lambda 0}$ – we obtain for $\Delta\Lambda$ a value, in (reduced) Planck units, of 6.58×10^{-123}, from which we then get $\frac{1}{\Delta\Lambda} = 1.52 \times 10^{122}$. (This latter value, unlike that of the spacetime four-volume $\mathcal{V}$, is in units of squared Planck length; this difference is unimportant, however, given our use of Planck units, in which the relevant quantities become dimensionless. The important thing is that $\frac{1}{\Delta\Lambda}$ and $\mathcal{V}$ be equal in *magnitude*, though of course the two need to be calculated differently.) What we need, then, is $\mathcal{V} = 1.52 \times 10^{122}$.

To obtain this result, we first need to decide how much of $\mathcal{V}$'s size to attribute to inflation and the pre-inflationary era, on the one hand, and how much to ascribe to post-inflationary (p)reheating, on the other hand. In [24], up to 3 e-folds of preheating are allowed, so we here make a conservative assumption of 1 e-fold of preheating. And given our choice of $t_{preh} = 10^{-32}$ s, all that is left is to calculate what value of the universe's spatial radius r (at t_{preh}) will yield the desired "$\mathcal{V} = 1.52 \times 10^{122}$." The result obtained here is r $\simeq$ 34 m, which (a) lies well within the range of allowed r-values [46], and (b) is (as desired) significantly larger than the minimum value allowed, which is on the order of 1 m [46]. Thus, in agreement with the account given here, according to which $\Delta\Lambda$'s value is "post-determined" [39] by the four-volume $\mathcal{V}$ when (p)reheating ends, there does exist a suitable value of $\mathcal{V}$ from which an observationally correct $\Delta\Lambda$-value can be calculated; and so, the present account is able to explain (non-anthropically) $\Delta\Lambda$'s measured value.

Admittedly, the above values of $\Omega_{\Lambda 0}$ and H_0 are not universally agreed upon. But even so, current observational bounds on $\Omega_{\Lambda 0}$ and H_0 restrict these parameters to a very narrow range, in the sense that any variation of them within this range has only a slight effect on the resulting value of $\Delta\Lambda$. It is therefore easy to maintain conformity with $\Delta\Lambda$'s measured value, even for different allowed values of $\Omega_{\Lambda 0}$ and H_0, by simply making a small adjustment in r's assumed value. Other adjustments can be obtained by varying the number of preheating e-folds, or by making different assumptions regarding when inflation and preheating end. The point is that there is some flexibility in choosing various parameter values here.

6. Conclusion

We conclude by touching briefly on some ideas that involve treating the universe in systems-theoretic terms. Consider first the idea – mentioned earlier in passing – of evolution at the edge of chaos. An important and distinctive feature of systems which undergo such evolution is that they display complexity at all scales [22]. If we take the universe to be a system of interest, this suggests that the universe's ability to foster the emergence of a rich diversity of physical, chemical, and biological phenomena may be linked to its being at the edge of chaos, or near a "critical point," itself. (For an application of the idea of "self-organized criticality" to particle physics, see [49].) In the context of BCGT, a vanishing CC places the universe at the edge of chaos, or catastrophe; and we have suggested that the transition from the vacuum-energy-cancellation mechanism of [21] to VES represents an instance of cosmic evolution at the edge of chaos. The fact that the CC's value is very close to zero suggests that the universe as a whole remains near the edge of chaos.

On a somewhat different note, it is interesting that the process described here, in which a CC that has vanished is replaced by a new nonzero Λ, bears some resemblance to the process of "phase space signal processing" [50], in which an initial signal or input – which in the present case consists of a "distress signal" that emanates from spacetime and is prompted by the impasse induced (using BCGT) by the CC's cancellation – is received and processed in a higher-dimensional phase space (or more specifically, for the case discussed here, in the extra dimensions associated with momentum space), where it is then transformed into an output signal that responds to the original input signal. Here this output consists of information that is used to determine a specific nonzero value for a new Λ, thereby making a crucial contribution to this Λ's emergence.

The process by which this output signal is generated or produced amounts to a kind of "measurement process" that brings forth, analogously to the case of quantum measurements, a *new* value for Λ. In the context of the BCGT of [1], the new nonzero CC is needed to ensure that spacetime does not become totally flat, since flatness here would mean "no local gravity" and hence the absence of "a meaningful gravity theory" [2, sec. 3.4]. And because the transition to a world without gravity is a seemingly impossible task for the universe – since physically implementing such a transition requires a severe violation of the First Law of Thermodynamics – ensuring gravity's non-disappearance here *via* the creation of a new nonzero CC represents, as noted earlier, a kind of cosmic self-healing.

As a final note, our key proposal – namely, that the CC's observed value is determined by *information* acting as a template that "guides" the relevant four-form fluxes and their ratio – involves the view that information can actively influence the behavior and properties of physical systems. This view is derived from and supported by the idea of "active information" developed by Bohm and Hiley [51] (see also [52], chapters 1, 3, and 10).

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