

Article

A Universe that Does Not Know the Time

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Abstract: In this paper, we propose that cosmological time is a quantum observable that does not commute with other quantum operators essential for the definition of cosmological states, notably the cosmological constant. This is inspired by properties of a measure of time—the Chern–Simons time—and the fact that in some theories it appears as a conjugate to the cosmological constant, with the two promoted to non-commuting quantum operators. Thus, the Universe may be “delocalised” in time: it does not *know* the time, a property which opens up new cosmological scenarios, as well as invalidating several paradoxes, such as the timelike tower of turtles associated with an omnipresent time line. Alternatively, a Universe with a sharply defined clock time must have an indeterminate cosmological constant. The challenge then is to explain how islands of localized time may emerge, and give rise to localized histories. In some scenarios, this is achieved by backward transitions in quantum time, cycling the Universe in something akin to a time machine cycle, with classical flow and quantum ebbing. The emergence of matter in a sea of Lambda probably provides the ballast behind classical behaviour.

Keywords: quantum gravity; quantum cosmology; definitions of time

1. Introduction

The concept of time is fundamental in the formulation of the laws of physics. For this reason, as physics has become more abstract and distant from everyday experience, our intuitive notion of time is often contradicted by more formal definitions. In Relativity, time is ontologically placed on the same footing as space, so that our cherished sense of “flow of time” is lost, since there is no flow of space. In Canonical Quantum Gravity, time disappears from the picture altogether, leading to a number of outstanding problems¹.

Another situation far-removed from our daily experience is the beginning of our Universe. This is a place we have never been to, yet we insist on extrapolating to it concepts that have only been tested in more familiar circumstances. Not surprisingly, paradoxes arise [4–8], often related to the issue of first cause, not the least in bouncing models: how many cycles were there “before” ours? Such considerations rapidly degenerate in a timelike tower of turtles [9], in different guises in different models. These are tied to the dogma of an omnipresent *time line* presiding over the life of the Universe. However, why would this concept of time apply to extreme situations, such as the Big Bang or the handover of one cosmological cycle to the next?

¹ We are not attempting to solve the problem of time in quantum gravity in this paper. We refer the reader to extensive early literature [1–3] on the subject.

In this paper, we insist on the premise that cosmology is characterized by the condition that there is nothing outside the Universe. As a result, any reference to time in a cosmological model must refer to a reading of a physical clock, that is, a function of observables characterizing dynamical degrees of freedom *inside* the Universe. With the loss of a preferred external or absolute time, there are diverse clocks which may be used for different purposes. Some depend partly on matter degrees of freedom, others depend solely on the gravitational degrees of freedom.

The quantum nature of our world, and of gravity in particular, may therefore permeate our definition of cosmological time. In this paper, we propose that cosmological time is a quantum operator, which, at least in extreme circumstances, does not commute with other operators, namely the quantum cosmological constant. The state we come from (and which we are headed to, as it appears) seems to be a strongly squeezed quantum state sharply centred on $\Lambda = 0$, and thus delocalized in time.

In some phases of its life, our Universe may, therefore, be delocalized in time, in the same way that a quantum particle is delocalized in space if its momentum is sharply defined. If the Universe does not know the time, it cannot wonder about its first cause. It can also rewind and recycle without the usual problems of cyclic and bouncing scenarios, tied to the idea of an eternal time line. We develop this idea first with reference to a concrete theory [10], gleaning inspiration from the concept of Chern–Simons (CS) time [11] and the Kodama state [12] in Quantum Gravity (QG), then in greater generality. We stress that our conclusions are not wedded to the particular theory from which we start, but which nonetheless serves to motivate our proposal².

With this in mind, in Section 2, we start by examining a number of possible definitions of time, in tandem with the precept that nothing exists outside the Universe. We then focus on CS time, as a possible definition of time that survives QG. Past work is reviewed, and we highlight the most recent developments which have inspired this paper.

Even though the concept is prompted by QG, in Section 3, we initially examine CS time as a classical quantity. We find an intriguing result: the horizon problem of Big Bang cosmology, and the principle that it was solved in a non-standard primordial phase, amount to the idea that the Universe is a *two-way* loop in CS time, with “ebb” and “flow” of time related to these two phases. Periodicity is not required in these cycles. We stress the difference to standard closed time-like curves (e.g., [9]) where the arrow of time remains unchanged along the loop.

In Section 4, we then quantize CS time, taking our cue from the Kodama state of QG and the work of [10], but largely superseding its construction. In our picture, CS time and the cosmological constant, Λ , appear as non-commuting observables in an essentially kinematic Hilbert space³. Thus, a sharp state in Lambda must be delocalized in time. The ebbing of time could then be a *quantum fluctuation*, or a *quantum leap*, associated with the smallness of the cosmological constant, and the uncertainty in time it must entail.

That this can work to solve the horizon problem is demonstrated in Section 5, based on the uncertainty relation,

$$\Delta T^2 \Delta (I_P^2 \Lambda)^2 \geq \frac{1}{4} \quad (1)$$

² Indeed, we note that the idea that the cosmological constant is conjugate to a measure of time has appeared before, in the context of unimodular gravity [13–15]. There, the conjugate measure of time is the four volume to the past of a three slice.

³ We use the term “kinematic” to mean without the usual canonical dynamics, i.e., without a Hamiltonian over a classical phase space, from which a Poisson bracket or commutator structure (upon quantization) generates a time evolution. The point is that, since there may be situations in which there is no time in the conventional sense, we should also be prepared to eschew the conventional concept of dynamics. We do, however, postulate commutators, and these have *kinematical* implications, such as uncertainty relations and the form of eigenfunctions in terms of representations diagonalising the complementary variable. In this paper, we do not use the term kinematical in the sense it has acquired in a specific community—of something akin to “unphysical because it does not commute with the quantum constraints.” The commutation relations of our operators also do not come from classical Poisson bracket analogues. Note that this structure does not preclude the existence of a base space (where these kinematic quantities act as parameters, or measures) which is itself dynamical, and endowed with a Hamiltonian, such as in the constructions of [16]. The base space may or may not be quantized.

(where $l_p^2 = 8\pi\hbar G$) and variations thereof (here T could be a function of CS time, or any other similar measure). The challenge is then to explain the onset of classicality, and cycle one phase into the other, and this is addressed in Section 6. A working model is produced, where matter (i.e., energy other than the cosmological constant) provides the ballast for the classical phase. The fact that the transition between the two is fuzzy should not bother us. After all, this model is all about losing and then regaining a conventional “time” line, defined in terms of a classical gravitational clock time.

A more philosophical digression is presented in Section 7 and we close in Section 8 with conclusions and an outlook.

2. Concepts of Time

Before we get to our proposals, we want to start with some words of caution. First, we have to be careful to distinguish several distinct notions of time. Some authors hypothesize that there is a fundamental, causal notion of time as an activity which continually generates new, future events from present events [17–20]. This notion of time is fundamental and irreversible [20–24]. Others instead hypothesize that no such fundamental time exists or that, if it does, it may not be directly connectable with the t 's in our equations. In any case, we must distinguish these hypothetical fundamental times from clock times, which are observable and which are at least in some circumstances connectable with the t 's in the equations of physics.

Whether or not there is an active, fundamental time, the dynamical equations of physics are supposed to generate correlations between observable quantities. Cosmology is characterized by the condition that there is nothing outside the Universe, hence if we want to refer to time in a cosmological dynamical equation, it must refer to a reading of a physical clock, which is to say, a function of observables characterizing dynamical degrees of freedom inside the Universe.

Since there is no preferred external or absolute time, there are diverse clocks which may be used for different purposes. Some depend partly on matter degrees of freedom; these may be called *matter clocks*. Others depend solely on degrees of freedom of the gravitational degrees of freedom; we refer to these as gravitational clocks.

In General Relativity, in the cosmological case, with spatially closed boundary conditions, there are several natural gravitational clocks which are functions of degrees of freedom of the gravitational field. These typically require a foliation of the 3 + 1 dimensional spacetime into a one parameter family of spatial slices, Σ_t , labeled by an arbitrary parameter time, t . This reflects a fixing or breaking of the four dimensional diffeomorphism invariance, by a physical gauge fixing condition, also a functional of degrees of freedom, to a product of $Diff(\Sigma_t)$ and reparametrizations of t . A clock time $T(t) = T(\Sigma_t)$ is a function of the three metric and extrinsic curvature on Σ_t .

What makes a good physical clock? We may try to list conditions, such as continuity, uniqueness and monotonicity, but with the understanding that there is no perfect clock that satisfies them in all regimes and conditions, especially once quantum effects are taken into account. In fact, in this paper, we will be interested in cases where these natural conditions we might impose on a good clock are violated by quantum effects.

Indeed, as a physical clock is a function of physical degrees of freedom, it will fail to commute with some other degrees of freedom. In other words, for any notion of physical clock time, there will be always some cost to knowing what time it is. We insist that this is good, not bad, because there may be cases in which the cost of knowing the time implies certain features of the quantum phases of the Universe's evolution.

With this in mind, we would like to focus here on a particularly interesting gravitational clock time, which is the Chern–Simons time [11]:

$$T_{CS} = \Im(Y_{CS}), \quad (2)$$

where

$$Y_{CS} = \int A^i \wedge dA_i + \frac{1}{3} \epsilon_{ijk} A^i \wedge A^j \wedge A^k, \tag{3}$$

where A^i is the Ashtekar connection one form and \Im means the imaginary part. We point out that T_{CS} has three features, which make it a particularly interesting probe of the quantum phases of our Universe:

1. For homogeneous or nearly homogeneous Universes, in a spatially flat slicing, T_{CS} measures the ratio of the Hubble volume to a co-moving volume (see the next section). That means that, when you can measure the Chern–Simons time over an interval, you learn the two most important facts which situates your moment in a cosmological history: how large the horizon is and whether it is growing or shrinking.

Furthermore, it is immediately apparent that, if there are eras in the evolution of a quantum cosmology in which T_{CS} is subject to large uncertainties or large quantum fluctuations, they are not going to fit into the existing catalogue of cosmological scenarios.

2. In a very natural class of extensions of General Relativity, studied in [10], the cosmological constant Λ becomes a dynamical variable. In the quantum theory, $\frac{\hat{1}}{\Lambda}$ is in fact the operator conjugate to \hat{T}_{CS} .
3. In these models [10], the commutator of $\hat{\Lambda}$ and \hat{T}_{CS} is proportional to $l_{Pl}^4 \hat{\Lambda}^2$, leading to uncertainty relation:

$$\Delta \Lambda^2 \Delta T_{CS}^2 \geq \frac{1}{4} \left(\frac{16\pi \hbar G}{3} \right)^2 \langle \hat{\Lambda}^2 \rangle^2. \tag{4}$$

We see in these simple relations hints of novel scenarios for the evolution of the Universes through successions of classical and quantum phases. When, as now, $\hbar G \langle \hat{\Lambda}^2 \rangle$ is small, Λ and T_{CS} are simultaneously measurable and classical General Relativity suffices. However, in a quantum phase in which $\hbar G \langle \hat{\Lambda}^2 \rangle$ is large, one or both of Λ and T_{CS} are undeterminable and subject to large quantum fluctuations.

3. Chern–Simons Time and the Horizon Problem

We note that, for a general Friedmann Universe, in the cosmological frame (or for a flat slicing for a de Sitter Universe), the Ashtekar connection and its conjugate electric field are given by [25–27]:

$$A_a^i = iHa\delta_a^i, \tag{5}$$

$$E_i^a = a^2 \delta_i^a. \tag{6}$$

It is then interesting to note that, as pointed out above, when evaluated for a FRW Universe, in a spatially flat slicing, CS time becomes the number of Hubble volumes fitting inside a given comoving region, that is:

$$T_{CS} = H^3 V \propto (Ha)^3, \tag{7}$$

where a is the expansion factor, and $H = \dot{a}/a$ is the Hubble parameter. Two remarkable conclusions can be drawn at once. **Firstly**, it would appear that the standard Big Bang Universe is going backwards in CS time. Indeed, this retrograde “motion” of time is nothing but a statement of the horizon problem of Big Bang cosmology. Conversely, any solution to the horizon problem (regardless of its nature) can therefore be reinterpreted as the statement that, in the “early” Universe, CS time moved forward enough so that it could rewind to now during the standard Big Bang phase. **Secondly**, the fact that the Universe recently “started” accelerating suggests emphasizing the similarities between the two accelerating phases (“current” and “primordial”). Could the Universe be cyclic (in some variables) in the sense that it undergoes a pulsation of forwards and backwards CS time? It is tempting to envisage

the Universe as a closed loop of ebb and flow in CS time. If so, the “recent” “start” of acceleration is nothing but a turning point of the tide⁴.

We stress that cyclic does not necessarily mean periodic. The time variable might be an angular variable (with half the angles describing ebb and the other half the flow, for example $T_{CS}/T_{CSmax} = \cos \theta$, but the other variables do not need to return to the starting point. The cosmological constant, for example, could classically depict a spiral (using it as the radial variable). As we will see in the next section, the situation can also be more complex and interesting quantum mechanically.

We could modify the definition (2) by a multiplicative minus sign, resulting in:

$$T_{CS} = -\Im(Y_{CS}). \tag{8}$$

In effect, the choice between definitions (2) and (8) amounts to a definition of the arrow of CS time. With choice (8), cosmological CS time is negative, goes forward during the standard Big Bang phase, and back during the accelerated phase. With this alternative definition, the discovery that we are accelerating nowadays implies that the reflux of time has started.

Note that no measure of time, including T_{CS} automatically dominates over the others. Thus, when the evolution of T_{CS} reverses, this does not imply that other measures of time also reverse. Different clock times are useful for different purposes. In particular, the thermodynamic and electromagnetic arrows of time do not necessarily reverse when T_{CS} reverses.

Ultimately, the choice of sign in the definition of time will depend on its relation with the cosmological thermodynamical arrow. Assuming entropy can be globally defined on a cosmological scale, would the thermodynamical arrow of time coincide with the arrow of CS time (in one of its two possible definitions)? If this were the case, flux and reflux models bypass a number of criticisms that might be levelled upon them. An accumulation of entropy from cycle to cycle would not be an issue, since the process we have envisaged is not a closed loop in time: it is as an ebb and flow of time, with similar implications for entropy.

Unfortunately, this argument does not apply because the thermodynamic and Chern–Simons arrow of time are not coupled. However, what if the “ebb” of Chern–Simons time took place in a phase dominated by quantum geometry? The second law might appear to be violated during such a phase. We will revisit this matter later in this paper, when we discuss quantum time.

For the sake of definiteness, we shall assume that, for the rest of this paper, the sign convention (8), which is CS time, flows forward in the standard Big Bang (BB) phase, ebbing back in an accelerated phase. Given that the definition depends on the comoving region considered, we should also factor out its comoving volume $V_c = V/a^3$. With these refinements, we can therefore redefine CS time as:

$$T_{CS} = -\frac{H^3 V}{V_c} = -(Ha)^3. \tag{9}$$

We can now relate T_{CS} and cosmic time t . For equation of state $w \neq -1$, we have:

$$T_{CS} \propto -t^{-\frac{1+3w}{1+w}} \tag{10}$$

⁴ The strange grammar of this paragraph is a reminder that one should purge one’s thoughts from the unavoidable inconsistencies of our language, tied to the human experience of time. If T_{CS} is to be the only definition of time that can be extrapolated to the whole life of the Universe then expressions such as “early” Universe, or “motion” in time are misleading and inappropriate.

assuming an expanding Universe, i.e., $t > 0$. In the matter dominated epoch $T_{CS} \propto -t^{-1}$ and in the radiation epoch $T_{CS} \propto -t^{-3/2}$. The Milne Universe ($w = -1/3$) marks a stationary point in time (could loitering in CS time be interesting?). For a Lambda dominated model:

$$T_{CS} \propto -\exp(3Ht), \tag{11}$$

with H a constant⁵. As we see here, one may have two concepts of time, t and T_{CS} , which can be related classically; however, as we shall see in the next section, it could be that, in a quantum phase of the Universe, they become very different.

We close this section by noting that alternative definitions of time have been studied elsewhere [28], in the same context of a new *classical time*, in the sense that time is not promoted to an operator, with its Hilbert space of states, and incompatible observables. The latter, however, is the whole point of this paper, and this section is to be seen as a mere warm up to what follows.

4. Quantum Time

Having found a new realization for a cyclic Universe by means of a classical analysis, we now try to reframe it quantum mechanically. Could the CS time, which seems to ebb and flow in our Universe, do so quantum mechanically at least for part of the cycle? In what sense could time be quantum mechanical?

The CS functional appears in the wave function of the Universe in the connection representation, for a given ordering of the quantum Hamiltonian in the self-dual formalism. This wave-function is the so-called Kodama state [12]:

$$\Psi = \mathcal{N} \exp\left(\frac{3Y_{CS}}{2l_p^2 \Lambda}\right) \tag{12}$$

(where $l_p^2 = 8\pi G\hbar$) and it is known to suffer from all manner of problems, or at least open questions. Here, we take stock of the lessons from the Kodama state to motivate our proposal, without importing its problems. We note that we can split

$$Y_{CS} = Y_R + iY_I \tag{13}$$

with $Y_R^\dagger = Y_R$ and $Y_I^\dagger = Y_I$, so that both are candidates for observables a priori. Explicitly:

$$Y_R = \frac{Y_{CS} + Y_{CS}^\dagger}{2}, \tag{14}$$

$$Y_I = \frac{Y_{CS} - iY_{CS}^\dagger}{2i}. \tag{15}$$

The imaginary part of Y_{CS} gives us the CS time. The real part is associated with large gauge transformations, and is the source of the many deficiencies of the Kodama state [29].

In view of this, in this paper, we postulate a kinematic Hilbert space (in the sense spelled out in the Introduction) spanned by wave functions of the form:

$$\Psi = \mathcal{N} e^{iET}, \tag{16}$$

⁵ In the above, we have assumed expanding Universes only. In bouncing/cyclic scenarios, the relation between the direction of flow of T_{CS} and the horizon problem has to be revisited. As it happens, CS time continues to flow forward in the contracting phase, passing zero at the turnaround point. The ebbing of CS time happens fully during the bounce phase. We leave to a future publication a more complete discussion of this case.

with the usual inner product (delta function normalization)⁶. Modulo complex conjugation, these Ψ can be functionally seen either as eigenstates of the operator \hat{E} in the T representation, or as eigenstates of the operator \hat{T} in the E representation:

$$\Psi = \langle T|E \rangle = \langle E|T \rangle^* \tag{17}$$

Regardless of the representation, we can posit that the Hilbert space is endowed with the Hermitian operators \hat{E} and \hat{T} , satisfying commutation relations:

$$[\hat{T}, \hat{E}] = i \tag{18}$$

leading to a Heisenberg uncertainty principle between them:

$$\Delta E^2 \Delta T^2 \geq \frac{1}{4} \tag{19}$$

For the Kodama state, we have:

$$T = T_{CS} = Y_I, \tag{20}$$

$$E = \frac{3}{2l_p^2 \Lambda} \tag{21}$$

and so:

$$\left[\hat{Y}_I, \frac{1}{\Lambda} \right] = \frac{2}{3} i l_p^2, \tag{22}$$

with a possible representation:

$$\frac{1}{l_p^2 \Lambda} = -i \frac{2l_p^2}{3} \frac{\delta}{\delta Y_I} \tag{23}$$

In addition, we have:

$$H^2 = \frac{\Lambda}{3}, \tag{24}$$

as the Hamiltonian constraint of the *base* space (not to be confused with the kinematical space defining Λ and T ; see [16] and footnote 3). However, we shall allow for more general theories in the next section, both in terms of the allowed $E(\Lambda)$ and $T(T_{CS})$ functions (and their commutators) as well as the Hamiltonian constraint (24).

Regardless of details (to be addressed in the next Section), the point to take is that a measure of clock time on a cosmological scale could be promoted to a Hermitian operator, i.e., a bona fide quantum observable like any other. This is *quantum* time beyond the simpler idea of *discrete* time explored in some approaches [20,30]. Crucially, our quantum time becomes an observable subject to Heisenberg uncertainty relations, so that we cannot “know” the time and simultaneously quantities which do not commute with it. This is true even if these quantities classically evolve “in time”, and it is not surprising. Classically, the momentum of a free particle, p , is related by a simple formula (via $p = m\dot{x}$) to its position, x , but quantum mechanically this cannot be true.

We close this section with two comments. If the Universe can be in a state where it does not know the time, then thermodynamical arguments may break down. If we do not know the time, how can we know the arrow of time? It is hard to see how the usual thermodynamics constraints could apply.

⁶ Note that CS time is dimensionless, as is its conjugate “energy”, function of the dimensionless quantity $l_p^2 \Lambda$.

Finally, we note Pauli’s “theorem” [31] is certainly not valid here, where time is not the standard time, and its conjugate variable is not the Hamiltonian⁷.

5. A Model for Quantum Ebbing of Time

As we shall presently see (next Section), in a viable model, one must require that the presence of matter invalidates the argument in the previous section. However, *when Lambda dominates the energy density of the Universe* the argument should be valid⁸. It is then easy to build a model providing the necessary delocalization in CS time to rewind time enough to solve the horizon problem. Indeed, it is sufficient to choose:

$$T = T_{CS} = Y_L, \tag{25}$$

$$E = l_p^2 \Lambda. \tag{26}$$

One can then kinematically derive from (18) a Heisenberg uncertainty principle:

$$\Delta T_{CS}^2 \Delta (l_p^2 \Lambda)^2 \geq \frac{1}{4}. \tag{27}$$

In the quantum, Λ -dominated phase the Universe may be in the most general state in the Hilbert space spanned by (16). Some of these states are close to eigenstates of Λ , some are not. Those that lead to Universes like ours have a well defined Λ . Accordingly, CS time, as an incompatible observable, must be quantum mechanically undetermined, the more so, the sharper in Λ the state is.

Specifically, we can take:

$$\langle E | \alpha \zeta \rangle = \frac{1}{(2\pi \Delta_E^2)^{1/4}} \exp \left(-\frac{(E - E_0)^2}{4\Delta_E^2} - iE_0 T \right) \tag{28}$$

or

$$\langle T | \alpha \zeta \rangle = \frac{1}{(2\pi \Delta_T^2)^{1/4}} \exp \left(-\frac{(T - T_0)^2}{4\Delta_T^2} + iT_0 \right), \tag{29}$$

where $|\alpha \zeta \rangle$ represents a coherent squeezed state, with parameters:

$$\alpha = E_0 + iT_0, \tag{30}$$

$$\zeta = \frac{\Delta_E}{\Delta_T}. \tag{31}$$

This is known to saturate the bound (27). The fact that $l_p^2 \Lambda \ll 1$ suggests that we are in a wave packet centred at $\Lambda = 0$ but with a very small spread, of the order of the observed Λ :

$$E_0 = 0, \tag{32}$$

$$\Delta_E \approx l_p^2 \Lambda_{obs} \approx \gamma^4. \tag{33}$$

Here, γ is the relevant scale for instabilities and fine tuning:

$$\gamma = \frac{E_{CMB}}{E_P} = \frac{a_P}{a_0} \sim 10^{-32}, \tag{34}$$

⁷ Pauli’s theorem is the statement that no Hermitian operator \hat{t} can be found satisfying $[\hat{t}, \hat{H}] = i$, where \hat{H} is the Hamiltonian operator seen as a function of P and Q variables (as would be the case for \hat{t}). A number of assumptions are made, not necessarily valid, even before we note that the “theorem” would not be applicable here.

⁸ Clearly “domination” must mean Ω_Λ much closer to 1 than 0.7 to comply with observations (but see a possible loophole to this in the speculations presented in the Conclusions).

that is, the ratio between the CMB temperature and the Planck temperature, or the inverse redshift factor of the Planck epoch. For a pure radiation dominated Universe (i.e., ignoring the matter and Lambda domination epochs), the fine tuning behind the horizon, flatness and Lambda problems is given by powers of γ (specifically, a power of 4 for the Lambda problem). In terms of the CS time, we have a change in $|T_{CS}| \propto (aH)^3$ of the order of γ^3 since the Planck time because $aH \propto 1/a$, given that $H \propto \sqrt{\rho} \propto 1/a^2$ for radiation. Thus, the uncertainty in CS time implied by (27) and (33) was larger than needed to resolve the horizon problem

$$\Delta T_{CS} \approx \gamma^{-4} \gg \gamma^{-3} \tag{35}$$

(note that it matters little where the centre of the state T_0 is).

By choosing $T = T_{CS}^\delta$ with $\delta < 4/3$, the same result could have been obtained. More generally, if:

$$T = T_{CS}^\delta, \tag{36}$$

$$E = (l_P^2 \Lambda)^\beta, \tag{37}$$

with $\delta, \beta > 0$, we must have

$$\delta < \frac{4\beta}{3} \tag{38}$$

for a solution of the horizon problem to result from the fine tuning in Lambda. In deriving this result, note that, if x is a Gaussian with variance σ_x^2 and zero average, then $y = x^a$ is a (non-Gaussian) variable with zero average and variance

$$\sigma_y^2 = \frac{2^a \Gamma(\frac{1}{2} + a)}{\sqrt{\pi}} \sigma_x^{2a}. \tag{39}$$

In any of these models, the uncertainty in T_{CS} implied by the observed sharpness in Λ is sufficient for resolving the horizon problem.

In this scenario, the ebbing of time is therefore a quantum effect. Lambda leads to a solution of the horizon problem not because of classical acceleration (as in Section 3), but due to a quantum uncertainty principle. During the quantum phase, states sharp in Λ did not know the time. The Universe was not timeless, as in canonical quantum gravity: time *did* exist, but was not determinable. A quantum rewinding Chern–Simons time is therefore possible.

In summary, the probability of finding the system at some time T in the past is:

$$|\langle T | \alpha \zeta \rangle|^2 = \frac{1}{(2\pi \Delta_E^2)^{1/2}} \exp\left(-\frac{(T - T_0)^2}{2\Delta_T^2}\right). \tag{40}$$

Note that T_0 could be anything, but given that we are currently accelerating, it is probably “soon” (see below for the issues controlling the transition into and outside classicality). This probability is all that should be considered. It represents evolution outside time. It is a quantum leap in time, backwards, precisely because there is no time line. The philosophical implications will be discussed later in this paper.

6. Cycling the Classical and Quantum Phases

Given the proposal in the last section, the problem now is to ensure that the Universe has a classical phase. The counterpart of the “inflationary graceful exit” problem in our scenario is therefore coupled to the issue of the onset of classicality in a quantum system. In addition, we must explain how all the matter in the Universe appears in a Lambda dominated Universe (the analogue of “reheating” in inflation). The two issues—onset of classicality and generation of matter—are likely coupled.

The idea is to set up a cyclic model, with ebb and flow of CS time, in which the flow phase is classical but the ebbing is quantum, as described in the last section. The first decision to make is what

the triggers are for the transition between classical and quantum and vice versa. At least two options are available. The trigger could be a combination of the values of T_{CS} and of $l_p^2 \Lambda$ (specifically, for the observed value of $l_p^2 \Lambda$, quantum behaviour should be triggered for $|T_{CS}| < 1$ and $|T_{CS}| > \gamma^{-3}$). This possibility is very contrived. A more congenial possibility is that quantum behaviour is triggered by the value of Ω_Λ . Matter provides the classical ballast for our Universe.

The second decision to make is how to implement classicality, given the trigger. A possibility is to allow for the dimensionless Planck constant implicitly understood on the right-hand side of Equation (18) (and taken to be 1 there) to be a function of ρ and Λ via $\Omega_\Lambda = \rho_\Lambda / (\rho + \rho_\Lambda)$:

$$[\hat{T}, \hat{E}] = i\hbar(\Omega_\Lambda). \tag{41}$$

In the simplest model $\hbar(\Omega_\Lambda) = 0$ if $\Omega_{\Lambda-} < \Omega_\Lambda < \Omega_{\Lambda+}$, and $\hbar(\Omega_\Lambda) = 1$, otherwise (where $\Omega_{\Lambda+}$ represents the value of Ω_Λ at the point in the past where the Universe acquired its classical time line, and $\Omega_{\Lambda-}$ refers to the eschatological point in the future where it will turn quantum again). Time and Lambda then become knowable concurrently and classical evolution sets in, in one well defined regime. A quantum transition into the border of quantum and classical will be seen by the classical phase as initial conditions for purely classical evolution. This model not only explains the onset of classical time in a fundamentally quantum time system, but it also makes the snake bite its tail, if we want to create a cyclic Universe.

Naturally, the question remains: where did all the matter in the Universe come from? This may require more complicated cycles, including a transition from a higher, more natural value of Lambda. Matter (radiation) acts as the classical ballast but Lambda injects it when it changes. Recall that, with the addition of matter, the Hamiltonian constraints in the *base* space (previously Equation (24)) become:

$$H^2 = \frac{8\pi G}{3} \rho + \frac{\Lambda}{3}, \tag{42}$$

$$\rho a^{3(1+w)} + \rho_\Lambda = C. \tag{43}$$

We can then consider a cycle along the following lines:

- Classical phase. Localized time exists. Matter dominates Lambda. Time commutes with Lambda. We have the Big Bang Universe (BBU) as we know it. This may be represented as state:

$$|BBU\rangle = \prod_{i=BB}^{\Lambda \text{ dom}} |\Lambda\rangle \otimes |\rho_i\rangle \otimes |T_i\rangle, \tag{44}$$

starting from the first instant of “Big Bang” ($i = BB$; possibly the Planck scale), until the last, where Lambda dominates and the factorization of states for each instant i into time and Lambda is no longer possible.

- As expansion dilutes matter and Lambda dominates, a quantum phase ensues, with delocalized time. The Universe finds itself in a squeezed state $|\alpha\zeta\rangle$, as in Equation (28), with highly localized Lambda and delocalized time. Therefore, a finite amplitude exists for a transition to a state with T_- :

$$\langle T_- | \alpha\zeta \rangle = \frac{1}{(2\pi\Delta_E^2)^{1/4}} \exp\left(-\frac{(T - T_0)^2}{4\Delta_T^2}\right). \tag{45}$$

We assume that such a transition does take place, and it is a non-unitary process, akin to an “observation of time”.

- The state $|T_- \rangle$ itself can be written as:

$$|T_{-}\rangle = \int d\Lambda d\rho \langle \Lambda \rho | T_{-} \rangle | \Lambda \rho \rangle, \tag{46}$$

where ρ and Λ must satisfy the Hamiltonian constraint (43), which therefore allows for the creation of matter out of Lambda. Hence, there is a finite transition amplitude to the first state in (44). The part of the cycle delocalized in time, therefore, feeds into the time line of the BBU as an initial condition.

Many other possible cycles exist, alternating quantum and classical phases, with the production of matter from Lambda. In one way or another, they all have some tuning, and do not preclude the existence of states different from our Universe. The point is that a probability exists for our Big Bang Universe to be realized, and it is enough for this to be non-vanishing.

It could, of course, be the case that CS time is always quantum in our Universe and it is only the existence of matter that creates the *illusion* of classical time on a purely local level. This radical possibility—that in fact the Universe never knows the time—actually creates the simplest model.

7. Evolution without Time and the Emergence of Time

In this more philosophical section, we address a couple of interpretational issues, which, we stress, are decoupled from the cosmological model we have proposed.

One might have been critical of the fact that the Hilbert space we have proposed does not have dynamics or a Hamiltonian. We make no apologies for this. We are seeking a situation in which time localization can dissolve. Hence, there cannot be any dynamics in the usual sense because the framework for dynamics—localized time—is allowed to disappear. A kinematic Hilbert space is more appropriate to what we seek to do. For this reason, too, the Fock space (particle basis) is absent from our description, since its physical interpretation is missing. Coherent and squeezed states, and kinematic uncertainty relation are better tools under the circumstances. Note that the conjugate of time is not some Hamiltonian in our framework, but the quantum cosmological constant.

Evolution without time is then described by transition amplitudes (for example, (40) or (45)). This is a true “quantum leap” and strictly speaking we should only compute the amplitudes from when the system has left a localized-time island to when it arrived at another (which could be the same, but in its starting past). There, the state must appear as an initial condition for a Universe with a history. Outside of these islands, the Universe does not have a history because time is not localized.

How the usual localized time is to be represented in this formalism depends on whether $\hbar = 0$ in the classical phase, or just $\hbar \ll 1$. In the first case, time becomes localized and continuous. In the second, the wave function becomes the product of coherent states:

$$\Psi = \bigotimes_{i=BB}^{\Lambda \text{ dom}} |\alpha_i\rangle, \tag{47}$$

where the $|\alpha_i\rangle$ are eigenstates of the operator:

$$\alpha = E(\Lambda) + iT(T_{CS}), \tag{48}$$

each centred on a different instant. Each state has a finite spread $\Delta T = \hbar/4$. Thus, classical time monads emerge, that is, discretized time. Time in this sense has all the features of the first quantum theory (discretized quantities), without the elements of the second (interference and complementarity). It may be difficult to render these “thick instants” with constant thickness with respect to the usual cosmological time. This does not need to be seen as negative: it could have observational consequences.

8. Conclusion and Outlook: A Universe that Lost the Plot

In summary, this paper results from the realization that the beginning and the end of our Universe are far-removed from our experience; nonetheless, we have historically insisted on applying to them a

conception of time, which is essentially Newtonian, that has only been tested here and now. Predictably, a number of unsavoury paradoxes have been found. In cyclic cosmological models, for example, there is always the threat of an accumulation of entropy [4]. The issue of recurrence provides the perfect metaphysical nightmare [5,6,8]. More generally, one has to face up to the issue of “first cause”: how many cycles “preceded” ours? Such considerations apply in different forms to many cosmologies, cyclic or not, and invariably lead to well-known timelike towers of turtles, with some notable exceptions (e.g., [9]).

Here, we have investigated the consequences for these puzzles of a simple assumption: that quantum mechanics applies to the whole Universe—and everything in it—including the clocks that we use to measure time⁹. Time must hence be associated with a physical degree of freedom, a clock, whose value is represented by a quantum operator. Because there will then be other observables that fail to commute with it, there will be a cost to knowing what time it is. Our point has been that this cost is also an opportunity to find new ways to solve the major cosmological puzzles. Because our argument is quite general, the main alternative would be to posit that quantum mechanics does not apply to the Universe as a whole.

The problem of first cause for our Universe is closely linked to the notion of a “time line” applying to the whole life of the Universe. However, why would such a concept of time persist in extreme situations, such as the start of our Universe, or its regeneration into a new cycle? As Hartle and Hawking’s no boundary proposal illustrates [33], a radical change in the notion of time can simply erase the problem of first cause. In Hartle and Hawking’s proposal, this is achieved by a signature change. In this paper, we proposed that cosmological time is a quantum operator, which, at least in extreme circumstances, does not commute with other operators, namely the quantum cosmological constant. The state we come from (and which we are headed to) is a strongly squeezed quantum state sharply centred on $\Lambda = 0$, and, thus, delocalized in time.

In some phases, our Universe may, therefore, “lose the plot”. If the Universe does not know the time, it cannot worry about its own first cause. It can also rewind and recycle bypassing the problems tied to the idea of an eternal time line. Asking for a first cause for our Universe becomes akin to asking what “supports” the Earth? Chains of elephants, turtles, pillars and other animals and objects were once invoked to answer this question. They become embarrassingly unnecessary as soon as space is perceived differently, without “up” and “down” (for example, if Earth is seen as a floating disk, as it is believed Anaximander was the first to appreciate). Likewise, once time is reevaluated along the lines proposed in this paper, the question of first cause vanishes.

Losing localized time in a way is like the colloquial “losing the plot”, but this does not entail a free for all. It means describing the evolution in terms of quantum transitions, even if these are backwards in time. In this sense, the idea of “quantum leap” is perfectly embodied by the proposal in this paper. Regardless of the details of the implementation, this paper highlights the basic flaw behind the usual metaphysical and thermodynamical puzzles. In our concrete implementation, the delocalization in time responsible for our origin and ultimate fate is intimately tied to the observed small value of the cosmological constant. This “temporal delocalization” is very different from time disappearing. It is about time becoming quantum mechanically ill-defined. There is a classical definition of time, but it cannot always be sharp because of the laws of quantum mechanics. An entirely new picture of the Universe emerges, as a result.

The challenge then is to explain how, in a sea of Lambda, islands of localized time can appear. In this paper, we suggested a possibility, linked to the Heisenberg algebra of the theory. Other possibilities exist and will be explored elsewhere. For example, it could be that the inner product of the Hilbert space is dynamical, rendering the effective dimensionality of the Hilbert space of states dynamical too, allowing for time and Lambda to coexist when matter dominates Lambda, but not

⁹ For another approach to a quantum time, see [32].

otherwise. As we have speculated, it could also be that time is always quantum in our Universe and it is only the existence of matter that creates the illusion of classical time on a purely local level. This radical possibility—that the Universe never actually has a fundamental plot—would in fact lead to the simplest and least fine tuned model.

Beyond this challenge lies the promise of reaping further rewards, beyond the philosophical ones. Time and space become ontologically distinct in our proposal, but this does not mean that one must be confined to the homogeneous Universe approximation. Indeed, the CS functional can be (and has been) computed for perturbed Universes [26], where it still provides a measure of time. The implications for primordial density fluctuations and tensor modes will be discussed elsewhere, but clearly they afford us the best chance of an observational method for distinguishing this scenario from others. The eschatology of our model is dramatically different from its alternatives, but predictions related to fluctuations would undoubtedly be a more practical method for testing our model. Once the work on fluctuations is carried out, it is also possible that novel insights into the cosmological constant problem are found, beyond those discussed in this paper. More generally, our approach can be replicated regarding other constants of Nature and their tuning (with or without the inclusion of time in the gallery of quantum operators). Work along these lines has already been started [16], with interesting first results.

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