Cosmological constant caused by observer-induced boundary condition

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Abstract

The evolution of the wave function in quantum mechanics is deterministic like that of classical waves. Only when we bring in observers the fundamentally different quantum reality emerges. Similarly the introduction of observers changes the nature of spacetime by causing a split between past and future, concepts that are not well defined in the observer-free world. The induced temporal boundary leads to a resonance condition for the oscillatory vacuum solutions of the metric in Euclidean time. It corresponds to an exponential de Sitter evolution in real time, which can be represented by a cosmological constant \( \Lambda = \frac{2\pi^2}{r_0^2} \), where \( r_0 \) is the radius of the particle horizon at the epoch when the observer exists. For the present epoch we get a value of \( \Lambda \) that agrees with the observed value within 2\( \sigma \) of the observational errors. This explanation resolves the cosmic coincidence problem. Our epoch in cosmic history does not herald the onset of an inflationary phase driven by some dark energy. We show that the observed accelerated expansion that is deduced from the redshifts is an ’edge effect’ due to the observer-induced boundary and not representative of the intrinsic evolution. The new theory satisfies the BBN (Big Bang nucleosynthesis) and CMB (cosmic microwave background) observational constraints equally well as the concordance model of standard cosmology. There is no link between the dark energy and dark matter problems. Previous conclusions that dark matter is mainly non-baryonic are not affected.

1. Introduction

The cosmological constant had to be reintroduced as a free modeling parameter after the unexpected discovery of the cosmic acceleration in the end of the 1990s through the use of supernovae type Ia as standard candles (Riess et al 1998, Perlmutter et al 1999). Its small but non-zero positive value has since been regarded as one of the great mysteries of contemporary physics (cf Binétruy 2013). It is some 120 orders of magnitude smaller than one would expect for vacuum fluctuations in quantum field theory. Usually it is interpreted as representing some new kind of physical field, referred to as ‘dark energy’, but its appearance as a constant would then imply that our present time is singled out in cosmic history as exceptionally special. The ’Now’ would signal the onset of an inflationary phase driven by the dark energy for all eternity, although in the past this energy was insignificant by many orders of magnitude. This would contradict the Copernican Principle, which states that we are not privileged observers. The issue is generally referred to as the ’cosmic coincidence problem’.

The possible physical origin of the cosmological constant has been addressed from a variety of directions since the discovery of the cosmic acceleration, e.g. by Velten et al (2014), Padmanabhan and Padmanabhan (2014, 2017), and Lombriser (2019). Recently (Stenflo 2018, 2019, 2020) it has been shown that the observed value of the cosmological constant can be predicted without the use of any free parameters or modifications of Einstein’s equations, if the observed cosmic acceleration is caused by an observer-induced boundary condition instead of by some new kind of physical field. The boundary constraint affects the redshift pattern that surrounds...
each observer, in a way that can be described by a cosmological constant. The so induced cosmological constant does not herald the onset of a new inflationary phase, which would make our present epoch special.

While the idea that the cosmological constant could be related to boundary conditions is not new (e.g. Hayakawa 2003, Banks and Fischler 2018, Gaztañaga 2020), the earlier treatments are conceptually very different and have not had much predictive power. What fundamentally sets the present approach apart is the observer-induced nature of our boundary condition. While the analytical expression for the cosmological constant was derived in our previous papers on this topic, starting with Stenflo 2018, the viability of the theory has remained undetermined, because the appropriate cosmological framework that would allow confrontation with the observational constraints has been missing. To address this we need a new conceptual interpretation of the meaning and physical implications of the observer-induced boundary condition. It is done in the present paper. Although the resulting theory is found to be conceptually very different from that of standard cosmology, we show that the BBN (Big Bang nucleosynthesis) and CMB (cosmic microwave background) observational constraints are satisfied equally well as by the concordance model (while we also predict the numerical value of the cosmological constant, something that concordance cosmology is unable to do).

In section 2 we address the origin of the boundary condition and explain why it is a direct consequence of the presence of the observer, who causes a split of the time line between past and future. To derive the effect that the boundary has on the vacuum modes of the metric we need to make use of two complementary concepts of time: real and imaginary time. In section 3 we clarify the meaning of Euclidean or imaginary time and how it is related to thermodynamics and Hawking’s no-boundary proposal for the origin of the Universe. With this background we derive in section 4 the theoretical expression for the cosmological constant $\Lambda$ that corresponds to oscillatory vacuum modes of the metric. Comparison with the observed value for $\Lambda$ shows nearly perfect agreement if $\Lambda$ is determined by the resonance mode that has a wavelength given by the conformal age of the Universe (in time units) or the radius of the particle horizon (in spatial units). Such a resonance expresses a periodic boundary condition across the bounded time line. In section 5 we clarify why it is a natural consequence of the observer-induced boundary constraint, and show how it is related to thermodynamics. The resonance condition implies that the value of the cosmological constant is tied to the conformal age $\eta_i$ of the Universe, such that $\Lambda \sim 1/\eta_i^2$.

This leads to a different cosmological framework with implications for cosmic history, as explained in section 6. For the interpretation of observational data with this new framework we need to distinguish between the ‘intrinsic’ evolution of the Universe, and the ‘edge effects’ that the observer sees in the observed redshift-distance relation. These concepts are explained in section 7 together with plots that illustrate how the redshift pattern in the vicinity of each observer is modified by the observer-induced boundary. In a local region or ‘bubble’ around the observer, who defines the ‘edge’, one gets enhanced and accelerated expansion with properties that are described by the induced cosmological constant. In section 8 we explain why the new cosmological framework satisfies all the BBN and CMB observational constraints. We show that there is no link between the dark energy and dark matter problems. The long-standing conclusion that most of dark matter must be non-baryonic is not affected. Section 9 presents the concluding remarks.

2. Boundary condition from observer participation

To understand the origin of the boundary condition it is helpful to draw a parallel with the measurement problem of QM (quantum mechanics). The result of a measurement depends on the experimental or observational framework. While the underlying equations are not changed, the set-up constrains the solutions of the equations. Heisenberg’s uncertainty principle is a consequence of this. For instance, if the set-up constrains the accessible time interval, energy fluctuations will be induced. There is complementarity between spacetime and momentum-energy, between waves and particles, between the real domain and its Fourier counterpart.

In Einsteinian GR (general relativity) the space and time dimensions extend indefinitely. Time has no boundaries (except singularities, like the Big Bang in the cosmological case). This describes an objective, classical world that ignores the participatory role of observers. It makes GR incompatible with QM, where observer participation profoundly changes the nature of reality (collapse of the wave function, probabilistic causality, etc.).

The introduction of an observer brings a profound change to classical GR by implying a split between past and future, concepts that have no well-defined meaning in a world without observers. The presence of the observer unavoidably changes the observational framework. The time line gets truncated, because the future is not accessible, even in principle. Instead of dealing with an infinite time dimension, time is now bounded between the Big Bang singularity and the observer-defined new edge, the Now. In QM a finite time interval affects the vacuum energy. The bounded cosmological time line has analogous consequences (although they are different, as clarified in section 5).
In the next sections we will show how the observer-induced temporal boundary affects the vacuum wave modes of the metric. Thus only modes with periodic boundary conditions in the Euclidean (imaginary time) representation are allowed. Oscillatory modes in imaginary time correspond to de Sitter type exponential evolutions in real time. The resonance condition, which follows from the boundedness of the time line, implies the existence of a $\Lambda$ term with a magnitude that is found to agree with the observed value within about 2%, without the use of any free parameters.

There has been considerable controversy about the use and physical meaning of imaginary time, after Hartle and Hawking (1983) introduced it to eliminate the initial singularity. Hawking has repeatedly referred to this idea as the ‘no-boundary proposal’ for the origin of the Universe (cf Hawking 1982, 1984). He nevertheless remained unclear about the physical reality of imaginary time versus its instrumentalist use as a mathematical tool without real physical meaning (cf Deltete and Guy 1996). Our application of imaginary time to successfully predict the observed value of the cosmological constant leads us to a somewhat different viewpoint, which is conceptually similar to the wave-particle complementarity in QM.

3. The multifaceted nature of time

The metric of a homogeneous, isotropic, and flat universe can be expressed in terms of three time concepts: proper time $t$, conformal time $\eta$, and Euclidean conformal time $\tau$:

\[
\begin{align*}
ds^2 &= -c^2dt^2 + a(t)^2(dr^2 + r^2 d\Omega), \\
ds^2 &= a(\eta)^2(-c^2d\eta^2 + dr^2 + r^2 d\Omega), \\
ds^2 &= a(\tau)^2(dr^2 + dr^2 + r^2 d\Omega). 
\end{align*}
\]

The Lorentzian representation of the metric with signature $(-+++)$ is generally considered as the ‘correct’ representation, because it allows a covariant description with a geometric interpretation, according to which the Lorentz transformations have representations as rotations of 4D spacetime. The 4D ‘marriage’ of time with space that was introduced by Minkowski has been so powerful that it has led to the view that time is just another dimension like space (albeit with opposite sign in the metric signature). However, this view of time is rather restricted, because it overlooks the circumstance that time is profoundly different from space in several other ways: it has an arrow, future is not observable, time travel is impossible. In addition, time has a deep connection with thermodynamics, entropy, and the 2nd law. Since these fundamental aspects are not contained in the Lorentzian geometric description, it is incomplete and needs to be complemented by other representations. Euclidean or imaginary time is such a representation. It is also incomplete, because it does not allow a geometric interpretation of the Lorentzian coordinate transformations, but it is nevertheless physically relevant, because it provides a representation of other profound aspects.

The Euclidean representation reveals a deep connection between statistical mechanics and QFT (quantum field theory) and has been widely used, in the form of Euclidean field theory, to deal with critical phenomena and phase transitions in condensed matter physics (cf Zee 2010, Peeters and Zamaklar 2011). It also exposes a deep link between general relativity and thermodynamics, in a way that opens up a direct route to derive the temperature of black holes (cf Gibbons and Perry 1976, Zee 2010). Hawking saw its potential for a theory of quantum gravity, a theory without singularities. This is the idea and motivation behind his ‘no-boundary proposal’ (cf Hawking 1982, 1984).

We know that GR is incomplete, because it contains singularities (like Big Bang or the center of black holes), where the theory breaks down (Penrose 1965, Hawking and Penrose 1970). It has been shown (Hartle and Hawking 1983, Hawking 1984) that this break-down may be avoided with the help of an imaginary-time representation. Hawking’s viewpoint has been that time becomes imaginary in the trans-Planckian region as we approach the initial singularity. This has the consequence that the physical singularity gets transformed into a benign coordinate singularity (like that of the spherical coordinates at the north or south poles). Around the Planck era there would be a transition of time from imaginary to real, after which the cosmic evolution would proceed in the standard manner.

A major problem with Hawking’s viewpoint is that the mechanism, which is responsible for the transition from imaginary to real time, the so-called ‘join problem’ (cf Deltete and Guy 1996), has never been specified. As will be argued in the following sections, the join problem never arises in our different interpretation of imaginary time: both real and imaginary time are physically valid but complementary aspects of the same underlying reality. The situation is analogous to the complementarity between waves and particles in QM. Although seemingly incompatible, they are both valid complementary aspects of physical reality. In terms of this analogy, Euclidean time represents the wave aspects (because it allows a QFT representation with oscillating phase factors), while real time corresponds to the particle aspects (with the energy-momenta that drive the cosmic
expansion). We may also draw an analogy with optics, where the complementary aspects of absorption and dispersion (or amplitude and phase) are unified with the help of a complex refractive index.

4. Derivation of the expression for $\Lambda$

The conformal metric preserves all the angles and relations between spatial and temporal coordinates, including the light-cone structure of Minkowski spacetime. We need the conformal framework for the description of the global Fourier modes of the metric in a way that is unaffected by the differential distortions by the scale factor $a$.

Allowing for a cosmological constant $\Lambda$ (of so far undefined magnitude), the vacuum modes of the metric are governed by

$$R_{\mu\nu} - \Lambda g_{\mu\nu} = 0. \tag{2}$$

In the case of a homogeneous universe without spatial gradients, the weak-field approximation in the harmonic gauge (cf Weinberg 1972) gives us

$$\frac{1}{2} \varepsilon^2 \frac{\partial^2 g_{\mu\nu}}{\partial \eta^2} - \Lambda g_{\mu\nu} = 0. \tag{3}$$

The choice of a particular gauge does not restrict the validity of the equation, because such a choice merely represents a mathematical procedure to deal with redundant degrees of freedom to simplify the equations. In general relativity like in all of classical physics and abelian quantum physics, the choice of gauge has no physical significance.

Equation (3) does not have any oscillatory solutions when $\Lambda$ is positive (which it is observed to be), because the two terms in the equation have opposite signs. Wave solutions only exist if we switch to imaginary (Euclidean) time $\tau$, because the first term then changes sign to give us the equation for a harmonic oscillator.

It is convenient to convert equation (3) to the standard form of a harmonic oscillator:

$$- \frac{\partial^2 g_{\mu\nu}}{\partial \eta^2} + 2\varepsilon^2 \Lambda g_{\mu\nu} = \varepsilon^2 \frac{\partial^2 g_{\mu\nu}}{\partial \tau^2} + \omega_{\Lambda}^2 g_{\mu\nu} = 0, \tag{4}$$

where we have introduced the frequency $\omega_{\Lambda}$ of the harmonic oscillator that satisfies the equation. Identification gives

$$\Lambda = \frac{\omega_{\Lambda}^2}{2\varepsilon^2}. \tag{5}$$

Since

$$\omega_{\Lambda} = \frac{2\pi}{\eta_{\Lambda}}, \tag{6}$$

where $\eta_{\Lambda}$ is the period of the oscillations, we get

$$\Lambda = 2 \left( \frac{\pi}{\varepsilon \eta_{\Lambda}} \right)^2. \tag{7}$$

Let us use subscript $u$ to mark that the respective quantity refers to a certain epoch (when the age of the Universe is $t_u$ and the scale factor is $a_u$). If we for $\eta_{\Lambda}$ insert the value $\eta_u$ of the present conformal age that is derived from the concordance model, then equation (7) gives us a value of $\Lambda$ that agrees with the observed value within the observational errors. Note that the agreement is not just within an order of magnitude but within 2% of the observations. The implied equality $\eta_{\Lambda} \approx \eta_u$ is too precise to be dismissed as a fortuitous coincidence. It convincingly suggests that equation (7) must represent a resonance condition for the vacuum mode of $g_{\mu\nu}$ across the bounded $\tau$ interval (between the Big Bang and the Now). In the next section we will address the origin of this resonance.

Instead of temporal units we can express the resonance in terms of spatial units with the help of the radius $r_u$ of the so-called particle horizon. It is related to the conformal age through $r_u = c \eta_u$. This gives us the simple formula

$$\Lambda_u = 2 \left( \frac{\pi}{\eta_u} \right)^2 \tag{8}$$

for the cosmological constant, which applies to any epoch of cosmic history.
5. Periodic boundary condition and thermodynamics

Because the exponential (de Sitter) evolution in real time corresponds to an oscillating phase factor in Euclidean (imaginary) time, we can represent Euclidean time in terms of an angular coordinate. Due to the presence of the observer, the physically meaningful Euclidean time string \( \tau_u \) is bounded. Its length is the age of the Universe in conformal Euclidean time units. We can express it in terms of angular units such that its length is \( 2\pi \). This scaling corresponds to the application of periodic boundary conditions. The resonance can be expressed geometrically by wrapping \( \tau_u \) around the unit circle exactly once. Such a circular 'Euclidean world' is bounded while having no boundaries. In real, spatial units, the period or wavelength of the resonance equals \( \tau_u \), interval, or, in terms of the geometric picture, wrapping it once around the circle.

According to Euclidean field theory with its powerful applications in solid-state physics (cf Peeters and Zamaklar 2011), the phase factor across the finite interval with periodic boundary conditions in Euclidean time becomes the Boltzmann factor in real time. Thus

\[
e^{i \omega \tau_u/\ell} = e^{-i 
 \frac{\omega}{2} \pi / \eta_u}
\]

which implies that the bounded time string induces a temperature

\[
T_u = \frac{\hbar}{k_B \eta_u}.
\]

The equipartition theorem tells us that each degree of freedom of the system has energy \( \Delta E = \frac{1}{2} k_B T_u \). Denoting the restricted time interval by \( \Delta t \equiv \eta_u \), we see that equation (10) is equivalent to the Heisenberg relation

\[
\Delta E \Delta t = \frac{1}{2} \hbar.
\]

It expresses how energy fluctuations are induced in the system when the time interval that is accessible to the observer is restricted.

Due to the large magnitude of \( \eta_u \), the present value of \( T_u \) is about \( 10^{-20} \) K, which is entirely insignificant as compared with the ambient CMB temperature. It is much too small to play a role in driving the observed cosmic acceleration and should not be confused with the apparent energy density that is embodied by the cosmological constant \( \Lambda \). Although both \( T_u \) and \( \Lambda \) are induced by a finite time interval (the age of the Universe), they are fundamentally different. In particular the expression for \( \Lambda \) does not contain Planck's constant \( \hbar \). It is therefore not directly related to quantum physics.

The mode energy \( \hbar \omega_u \), which indicates how much the metric is disturbed, is about \( 10^{-61} \) in Planck units (because \( \eta_u \) is about \( 10^{61} \) in units of the Planck time). This justifies the use of the weak-field approximation, because we are dealing with fluctuations of very small energy. The magnitude of \( \Lambda \), however, does not depend on the fluctuation amplitude (which scales with \( \hbar \)) but depends exclusively on the value of the resonance frequency \( \omega_u = 2\pi / \eta_u \).

6. Implications for cosmic history

In cosmology it is convenient to express the matter and radiation energy densities of the stress–energy tensor \( T_{\mu\nu} \) on the right-hand side of the Einstein equation in terms of the dimensionless parameters \( \Omega_M \) and \( \Omega_B \), which represent the respective energy densities in units of the critical energy density that separates open and closed model universes. We are free to move the \( \Lambda_u \) term to the right-hand side and interpret it as a fractional mass-energy density \( \Omega_\Lambda \) given by

\[
\Omega_\Lambda(a_u) = \frac{c^2}{3H_u^2} \Lambda(a_u).
\]

\( a_u \) is the local (at redshift \( z = 0 \)) scale factor \( a(t_u) \) for the epoch of the given observer. Present-day observers are at epoch \( t_u = t_0 \) when the Hubble constant \( H_u = H_0 \), while the scale factor \( a_u = a_0 = 1 \) is normalized to unity.

In standard cosmology \( \Lambda \) is a true constant that is independent of epoch and \( a_u \). This is not the case when \( \Lambda \) is induced by our periodic boundary condition, because it tracks the age or size of the observable universe as expressed by equation (8). In spite of this tracking property it is important to understand that both \( \Lambda(a_u) \) and \( \Omega_\Lambda(a_u) \) do not depend on redshift \( z \) from the perspective of the observer at epoch \( a_u \). This may at first seem strange but becomes clear if we realize that \( \Lambda(a_u) \) and \( \Omega_\Lambda(a_u) \) do not represent physical fields but are emergent quantities from a boundary constraint. Let us clarify.

The values of \( \Lambda(a_u) \) and \( \Omega_\Lambda(a_u) \) are tied to the global resonance frequency \( \omega_u \), which applies to the totality of the observable universe at the epoch that is defined by \( a_u \). The musical tones that emanate from a violin string do not depend on position along the string, they represent a global property of the oscillating system. Quantum
numbers do not vary with position within the atom but represent resonances of the system. Similarly, \( \omega_{\nu}, \Lambda_{\nu}, \) and \( \Omega_{\Lambda} \) do not vary with spacetime position across the observable universe that is defined by epoch \( a_u \). Therefore, although they vary with \( a_u \) (which is a quantity that exclusively refers to redshift zero), they do not vary with redshift. When we change \( a_u \), we shift the zero point of the whole redshift scale (because the observer in an expanding universe is by definition always located at zero redshift).

If \( \Lambda \) were due to some physical field, then it would need to be independent of epoch and \( a_u \) (as it is in standard cosmology), because this is demanded by energy conservation together with the Bianchi identities. Since \( \Lambda_u \) is independent of redshift for any given epoch, the Bianchi identities are indeed satisfied across the entire 4D spacetime that is observable at that epoch. The boundary conditions (and consequently the cosmological constant) change when we move to a different observer epoch, but this change does not violate the Bianchi identities, because the boundary conditions are not governed by any continuity or energy conservation equation. Instead they are governed by the global resonance condition that depends on the conformal age of the Universe.

The solution of the Einstein equation for an isotropic, flat, and homogeneous universe can be written as

\[
H = H_u E_u(y),
\]

where

\[
y \equiv a / a_u = 1 / (1 + z)
\]

and

\[
E_u(y) = [\Omega_{M}(a_u)y^{-3} + \Omega_{b}(a_u)y^{-4} + \Omega_{\Lambda}(a_u)]^{1/2}.
\]

Let us for convenience define the dimensionless conformal age \( x_u \) of the Universe as the conformal age \( \eta_u \) in units of the Hubble time \( 1 / H_u \). Then

\[
x_u \equiv \eta_u H_u = H_u \int_0^{a_u} \frac{dr}{a / a_u} = \int_0^{1} \frac{dy}{y^2 E_u(y)}.
\]

With equations (8) and (12) it gives us a compact expression for \( \Omega_{\Lambda} \):

\[
\Omega_{\Lambda}(a_u) = \frac{2}{3} \left( \frac{\pi}{x_u} \right)^2.
\]

This seemingly innocent equation cannot be solved directly, because \( x_u \) on the right-hand side depends on \( \Omega_{\Lambda}(a_u) \) on the left-hand side. The value of \( x_u \) is calculated from the \( E_u(y) \) function, which in turn needs \( \Omega_{\Lambda}(a_u) \) to be defined. Equation (17) can however be solved by straightforward iteration. The procedure is described in detail in Stenflo (2020). The iterations converge quickly to a unique solution.

In particular, the iterative solution for the present epoch verifies that we get nearly perfect agreement with the observed value for \( \Omega_{\Lambda} \). Our theory gives us (without the use of any free fitting parameters) \( \Omega_{\Lambda} = 67.2\% \), which is within 2σ from the value 68.5 ± 0.7% that has been derived from data with the Planck satellite (Planck Collaboration et al 2020).

While \( \Lambda \) is a constant that is independent of \( a_u \) in standard cosmology, the value of the dimensionless parameter \( \Omega_{\Lambda} \) scales as \( 1 / H_u^2 \) and therefore varies steeply with \( a_u \). It was insignificant in the past but will dominate in the future. We happen to live at an epoch when \( \Omega_{\Lambda} \) is comparable in magnitude to \( \Omega_{M} \) (which constitutes the cosmic coincidence problem).

In contrast, \( \Omega_{\Lambda} \) as derived from our cosmic boundary constraint has a value that does not change with \( a_u \) unless the equation of state of the matter-radiation content of the Universe changes. For a universe with no matter and no radiation we would have \( \Omega_{\Lambda} = 66.3\% \) (which is somewhat different from the 67.2% that we obtain for the present epoch, because the contribution to the \( x_u \) integral from \( \Omega_b \) is not negligible). For a universe with no matter but only radiation (which is a good approximation for the early universe) we get \( \Omega_{\Lambda} = 93.1\% \) instead.

7. Intrinsic evolution and edge effects in the redshift pattern

In quantum mechanics the evolution of the wave function that is described by the Schrödinger equation represents an evolution that is undisturbed by the presence of observers. It describes a world that is deterministic with well-defined causality and no uncertainty. Let us for convenience refer to it as the ‘intrinsic’ evolution. It is unobservable. Once an observer is introduced, the description changes profoundly.

In analogy, the ‘intrinsic’ evolution of the scale factor \( a(t) \) in cosmology is governed by the Einstein equation for a world without observers. The insertion of an observer implies the introduction of a temporal boundary, an edge that generates a repulsive force as expressed by the induced \( \Lambda \) term. Note that the observer can be inserted at
any time, there is nothing special about the present epoch. The cosmological constant is an observer-induced effect for any epoch in cosmic history.

The repulsive force has two main effects: (1) It enhances the expansion rate in the vicinity of the edge (i.e., for small redshifts). (2) It accelerates the expansion in a local region or ‘bubble’ that surrounds the observer. These are ‘edge effects’ caused by the presence of a boundary. They are large in the vicinity of the boundary but vanish at large distances from it. They manifest themselves as a change in the local redshift pattern, a change that becomes insignificant for large redshifts. Let us now explore them in quantitative detail.

Retaining the assumption of zero spatial curvature, the intrinsic cosmological evolution without the presence of observers is a Friedmann universe, obtained from the concordance model by removal of the cosmological constant. The matter $M$, radiation $R$, and $\Lambda$ terms each contribute to the squared expansion rate $H^2$ with amounts $H_0^2 \Omega_{M,R,\Lambda}$. If we remove the $\Lambda$ contribution, the expansion rate will be reduced. Let us use subscript $F$ to distinguish the intrinsic, underlying Friedmann model from the model without subscripts that describes the observed universe. Then $H_0 < H$ in the vicinity of the observer. If $H_0$ denotes the value of $H_0$ for $a = a_0 = 1$, then

$$H_0^2 = H_0^2 (\Omega_M + \Omega_R) = H_0^2 (1 - \Omega_\Lambda),$$

where the values of $H_0$ and $\Omega_{M,R,\Lambda}$ are determined by the observational constraints (Planck Collaboration et al 2020). An alternative one can use the nearly identical value of $\Omega_\Lambda$ that is obtained from equation (17) of our theory, which automatically also gives us the value of $\Omega_M \approx 1 - \Omega_\Lambda$ that follows because $\Omega_\Lambda \ll 1$. Accordingly

$$H_0^2 = H_0^2 (1 - \Omega_\Lambda),$$

which uniquely defines the ‘intrinsic’, underlying (and unobservable) Friedmann model. It is (through its definition) fully consistent with the presently observed values for $H_0$ and $\Omega_\Lambda$.

Figure 1 shows the evolution of the inverse expansion rate of the intrinsic Friedmann model (dashed), compared with the present concordance model of standard cosmology (solid). The most striking feature of this plot is the abrupt onset of an inflationary phase for the concordance model, an exponential expansion with a rate that does not depend on the scale factor. We happen to live at a time in cosmic history when this sudden transition takes place. It has been considered as a profound mystery why our epoch is singled out for such a dramatic cosmic event. This mystery does not exist in our cosmology, because the predicted inflationary phase is an artefact of incorrectly interpreting the edge effect as a physical field (dark energy).

With our explanation of the cosmological constant as a boundary-induced effect we instead find that our epoch is not different from any other epoch, we are not privileged observers. The cause of the abrupt transition of the solid curve is the insertion of an observer (us) at the present epoch. It creates a boundary between past and future, concepts that do not have any precise meaning in the intrinsic, observer-free model. The strange
apparent onset of an inflationary phase does not represent what will happen in the future, because the future portion of the diagram lies beyond the temporal boundary and therefore has no physical meaning.

The difference between the concordance and intrinsic models vanishes the further we look back in time. As seen in figure 1, the two models are practically indistinguishable for \( \log a \lesssim -1 \). Near the epochs of decoupling (CMB formation, around \( \log a \approx -3 \)) and element synthesis (BBN processes, around \( \log a \approx -9 \)) there is no significant difference between the expansion rates of the two models. The cosmology that follows from our boundary-induced explanation of the cosmological constant therefore satisfies all BBN and CMB observational constraints in the same way and with equal precision as concordance cosmology.

Figure 1 is not a suitable representation of what the observer sees. The future region of the diagram (where \( \log a > 0 \)) is not observable. The scale factor \( a \) in the past region is only indirectly observable in the form of redshift \( z \), because \( 1 + z = 1/a \) for \( a \leq 1 \). In figure 2 we have therefore replotted the observable portion of figure 1 versus redshift \( z \). It better illustrates that we are dealing with an edge effect. In redshift space the edge is always located at \( z = 0 \), regardless of the choice of epoch \( t_o \) for the observer. All the observed cosmic acceleration relates to the edge (the observer at \( z = 0 \)), not to the intrinsic time in cosmic history, in contrast to the traditional interpretation of standard cosmology. Regardless of when in cosmic history the observations are made, our hypothetical observer will find a redshift-distance relation that looks as if an inflationary phase suddenly begins at that very epoch. Although we choose an arbitrary epoch with our ‘Gedankenexperiment’, the use of standard cosmology for the interpretation will always make the observer’s epoch seem extraordinarily special.

As seen from figure 2, the edge effect manifests itself as an enhanced expansion rate in the vicinity (for \( z \lesssim 3 \)) of the observer (whose existence defines the location of the boundary). It is an edge effect, because the enhancement vanishes asymptotically for redshift \( \geq 3 \). Note that the enhanced region does not have any location in the underlying, observer-free intrinsic spacetime. While the temporal location (the epoch) of the observer defines the boundary, the location in space is arbitrary. Regardless of spatial location, the observer is always surrounded by an enhanced expansion pattern in redshift space.

The magnitude of the edge enhancement effect is exclusively a function of the value of the boundary-induced dimensionless parameter \( \Omega_\Lambda(a_o) \), which is given by equation (12). It only depends on the equation of state of the matter-radiation content of the Universe. In the early, radiation-dominated universe \( \Omega_\Lambda(a_o) \approx 93.1\% \), which is substantially larger than the present value of 67.2\%. A larger value of \( \Omega_\Lambda(a_o) \) induces a larger edge effect. Figure 3 illustrates this by giving the relative enhancement, i.e., the ratio between the observed and intrinsic Hubble constants \( H \), as a function of redshift for two different epochs, the present (solid), and the BBN epoch when the photon temperature was 1 GK (dash-dotted).

The edge enhancement is a local phenomenon that does not affect the BBN or CMB physics, because the dynamical time scale that governs the BBN and CMB non-equilibrium processes is determined by the intrinsic (and unenhanced) evolution. This will be clarified in the next section.

\[ \text{Figure 2. Log of the inverse expansion rate } 1/H \text{ versus redshift } z \text{ for the concordance model (solid) and the intrinsic Friedmann model (dashed). The information content is the same as that of figure 1 for the observable portion of the Universe (where } a < 1 \text{). The enhancement of the expansion rate (which lowers the solid curve relative to the dashed one) is an edge effect, because it vanishes asymptotically for redshifts } \geq 3. \]
The edge effect not only manifests itself by enhancing the expansion rate, but also by accelerating it. An observer existing at an epoch referred to with index \( u \), when the scale factor \( a = a_u \), would find a cosmic acceleration parameter \( q = q_u(z) \) with a redshift distribution given by

\[
q_u(z) = \frac{0.5 \Omega_M(a_u)(1 + z)^3 + \Omega_k(a_u)(1 + z)^4 - \Omega_\Lambda(a_u)}{\Omega_M(a_u)(1 + z)^3 + \Omega_k(a_u)(1 + z)^4 + \Omega_\Lambda(a_u)}
\]  

Figure 4 shows the properties of this function for the same two epochs that were illustrated in figure 3: the Now, and the epoch when the photon temperature was 1 GK. It illustrates that the observer is always surrounded by an accelerating ‘bubble’, not only as discovered from supernovae observations for the present epoch (represented by the solid curve in the figure), but even more so in the early universe, because the observer-induced value of \( \Omega_\Lambda(a_u) \) was larger then. As we have acceleration where \( q \) is negative, the radius (in redshift space) of the accelerating ‘bubble’ is given by the \( z \) for which \( q \) has a zero crossing. This radius is larger (extending to \( z \approx 1 \)) for
a radiation-dominated universe than for the present universe (for which it extends to $z \approx 0.6$). Beyond the bubble the acceleration parameter $q$ quickly approaches the value it would have in the absence of observers, i.e., unity for a radiation-dominated, $\frac{1}{7}$ for a matter-dominated universe.

Although every observer is forever embedded in an accelerating region, this is a local (edge) phenomenon, which by itself does not properly solve the large-scale isotropy and homogeneity problem that has been the motivation for postulating the occurrence of a violent GUT-era inflation in the early universe. While there are other profound reasons to question the inflation hypothesis (cf. Penrose 2004, 2016), this topic is outside the scope of the present work.

8. Confirmation of the need for non-baryonic dark matter

In the preceding section we interpreted the boundary-induced enhancement and acceleration of the expansion as a local phenomenon that determines how the redshift pattern of the receding galaxies appears to the observer. It is an edge effect that does not alter the dynamical time scale that governs the non-equilibrium physical processes. As will be clarified below, the relevant physical time scale is the expansion time scale of the intrinsic model, which is free from observer effects. Because the expansion rate of the intrinsic model does not differ significantly from the concordance model during the BBN and CMB eras, both models will satisfy all observational constraints equally well. In particular, the conclusion that the fractional baryonic matter content as expressed by the parameter $\Omega_B$ is only about 5\% is unaffected by our boundary-induced explanation of the cosmological constant.

While it may appear natural, as we have done, to pick the time scale of the intrinsic model to represent the dynamical time scale, this choice needs to be questioned and properly justified, because it is neither obvious nor unique. It could for instance be argued that the edge effects should be included, that the dynamical time scale should be determined by the expansion rate that the observer experiences directly. Such a modified time scale would differ significantly from the time scale of the concordance model, which would have major consequences for the confrontation with the observational data: Would such an interpretation be compatible with all observational constraints? If this would turn out to be the case, would the parameter fit give a different value for $\Omega_B$? In particular, is it conceivable in principle to come up with a scenario, in which all dark matter would be baryonic?

The short answer to these questions is that a significantly changed cosmic expansion history would conflict with the observations. The observational constraints are only compatible with one of the options for the dynamical time scale, namely the time scale of the intrinsic, observer-free model. Alternative interpretations can be ruled out. We now know that the alternative time scales that were derived in the previous development stages of the theory (Stenflo 2018, 2020) do not qualify as a dynamical time scale. In our earlier treatments it was not clear, whether or not there could be some coupling between the dark energy and dark matter problems. We now understand that the two problems are not directly related. While this might seem obvious in hindsight, it is an important issue that needs to be clarified. In the following we will outline the arguments, which made these conclusions unavoidable.

For this it is sufficient to limit our focus on the BBN processes of helium and deuterium formation, without the need to enter into technical details. The arguments can be summarized as follows: If we for instance enhance the expansion rate (by assuming that the observer-induced edge effect is relevant for the non-equilibrium physics), then $\Omega_B$ has to be raised to maintain agreement with the observed deuterium abundance. In contrast, $\Omega_B$ must be reduced to maintain agreement with the observed helium abundance. Therefore it is impossible to satisfy both the deuterium and helium constraints at the same time with a single value for $\Omega_B$.

The final deuterium abundance that is asymptotically approached when all the other reaction rates have frozen out is primarily governed by the ratio $R_{pD}/H$, where $R_{pD}$ is the rate for the $p + D \rightarrow ^3\text{He} + \gamma$ reaction (cf. Mukhanov 2005), and $H$ is the Hubble expansion rate. Because $R_{pD} \sim \Omega_B$, we need to keep the $\Omega_B/H$ ratio approximately unchanged to maintain agreement with the observed deuterium abundance. This is the main reason why an enhanced expansion rate requires a higher baryon fraction according to the deuterium constraint.

The final helium abundance on the other hand depends on the freeze-out of the neutron abundance. This freeze-out depends on the expansion rate $H$ but not on $\Omega_B$. An enhanced expansion rate leads to earlier neutron freeze-out with higher neutron abundance. Normally all these neutrons get used up to build helium. In this case enhanced expansion rate would lead to excessive helium abundance. If however the conversion to helium could be delayed by a time of order 10 min or longer, then only a fraction of the frozen-out neutrons would be available for helium formation, because the rest would have disappeared before due to spontaneous decay. As the rate of helium formation scales with $\Omega_B$, the conversion process can be slowed down by decreasing the value of $\Omega_B$. This may be possible without violating the lower limit $\Omega_*$ for the allowed value of $\Omega_B$, where $\Omega_* \approx 0.4\%$ is the estimated fraction of luminous matter (in stars) in the Universe (cf. Peebles 1993). As it is an order of magnitude
smaller than the nominal value for $\Omega_B$, there may be ample room for adjustments of the value of $\Omega_B$ to slow down the rate of helium formation as needed.

While these examples show that it is possible to find independent fits to the deuterium and helium abundances as long as the change in expansion rate is not too large, a simultaneous fit to both cannot be obtained. For large modifications of the expansion rate we enter into different regimes, in which even separate fits to the observed helium or deuterium abundances cannot be found. The basic conclusion is always the same: Any significant departure from the expansion rate that is used in standard cosmology for the early (radiation-dominated) universe would lead to violation of the joint observational constraints. As shown in the preceding section, the expansion history that is described by the ‘intrinsic’ Friedmann model satisfies this requirement. It represents the only viable version of the boundary-induced theory for the origin of the cosmological constant, but it is a version that agrees with all the constraints equally well as the concordance model.

Note that the age of the Universe according to the intrinsic Friedmann model is 9.7 Gyr, significantly less than the 13.8 Gyr of the concordance model. It is the shorter, ‘intrinsic age’ that is the physically relevant one. The age of the concordance model is larger because it is affected by the presence of the observer-induced $\Lambda$, which is an edge effect that is not relevant for the dynamical time scale.

As a consequence of this analysis we can conclude that the dark matter problem is not linked to the problem of the dark energy (cosmological constant). The previously adopted low value for $\Omega_B$ is unaffected. Most of dark matter needs to be non-baryonic to be consistent with the observational data.

9. Conclusions

In a world without participating observers there is no cosmological constant, and the time line extends indefinitely into the future. This world is unobservable, because the introduction of an observer changes its structure by causing a split between past and future, concepts that do not have any precise meaning in the observer-free world. Because the future is fundamentally unobservable, the present represents a boundary, an edge of time. The existence of this edge constrains the solutions. The induced boundary effect is a repulsive force that surrounds the observer with a region of accelerated expansion and a redshift distribution that can be modeled with a cosmological constant.

The boundary has no location in space, only in time (the ‘Now’), as if an infinitely high potential barrier has been erected to block access to the future. The presence of this barrier disturbs the spacetime metric, which in the cosmological context is represented by the scale factor that scales with $1/(1 + z)$, where $z$ is the redshift. The disturbance is large for small redshifts, i.e., close to the edge, but vanishes with increasing distance from the boundary (as the redshift increases).

The value of the boundary-induced cosmological constant is independent of redshift and has no gradients in the observable spacetime. It therefore does not appear in the equation for energy conservation. As an observer-induced effect it is not a physical field, but it affects the way the Universe appears from the perspective of the observer. The relevant physics that governs the cosmic evolution, in particular the dynamical time scale, is described by the Einstein equation for an observer-free universe. It is represented by the ‘intrinsic’ Friedmann model without a cosmological constant. The BBN and CMB intrinsic time scales are indistinguishable from the time scale of standard cosmology, because the CMB and BBN epochs are sufficiently far from the present temporal boundary to be significantly affected by the cosmological constant in the concordance model. The cosmology that follows from the observer-induced interpretation of the cosmological constant therefore satisfies all observational constraints equally well as the concordance model. In particular this implies a reconfirmation of previous conclusions that most of dark matter is non-baryonic.

The formula equation (8) for the cosmological constant, $\Lambda = 2(\pi/\nu_0)^2$, represents a resonance that is a consequence of a periodic boundary condition for the finite region in Euclidean (imaginary) time. In analogy with the wave-particle complementarity in quantum physics, there is a complementarity between Euclidean spacetime, with its wave-like world of complex phase factors, and Lorentzian spacetime, with its particle-like world of evolving real amplitudes. Both representations express complementary aspects of time, which cannot be captured by either representation alone.

This leads us to a cosmological framework that does not contain any ‘cosmic coincidence’ problem. There is nothing special about the epoch in which we live, we are not privileged observers. There can be no parallel universes with alternative values of the cosmological constant, because logical consistency demands uniqueness.

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