The Temporal–Electromagnetic Substrate: Quantisation and Vacuum Structure in the Temporal–Density Framework

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Abstract

This paper extends the *Temporal–Density Framework* (TDFT) to the quantum domain by treating the temporal potential as a quantised scalar field within a unified temporal–electromagnetic substrate. The resulting *tadpole–free* potential establishes a stationary temporal vacuum without requiring an external spin–2 mediator, while the macroscopic line–density constant $\lambda = c^2/(2G)$ and the fine–structure constant α emerge as complementary invariants of the same field. The fine–structure constant follows directly from the Maxwellian TEM relations as the active impedance ratio of the vacuum, providing a continuous bridge between electromagnetic coherence and gravitational curvature. Linearisation yields causal propagation at c and an exact Schwarzschild correspondence in the static limit, demonstrating that general–relativistic curvature arises naturally from saturation of the temporal field's vacuum energy. The analysis confirms dimensional closure across $\{\alpha, c, G, \hbar\}$ and consolidates the TDFT as a single coherent description linking quantum coherence, electromagnetism, and gravitation through a common temporal substrate.

Contents

1 Introduction and Context

The *Temporal–Density Framework* (TDFT) provides a unified description of gravitation, electromagnetism, and quantum coherence through the invariant triad

$$\boxed{\alpha\, c\, \lambda = 1}, \qquad \lambda = \frac{c^2}{2G}, \tag{1}$$

where λ is the *linear density constant* and α is the *temporal coupling constant*. Previous releases of the framework (Main TDFT Paper, FSC Derivation, and Interpretive Overview) established that this relation reproduces general–relativistic curvature in the macroscopic limit and yields the observed fine–structure constant when the vacuum impedance of the electromagnetic field is interpreted as a temporal impedance of the substrate.

Objective of this paper. The present work extends that framework to the quantum domain by introducing the *quantised temporal–electromagnetic (QTEM) field*: a single substrate whose longitudinal (compressive) mode gives rise to gravitational curvature, while its transverse (shear) mode reproduces the electromagnetic field. The analysis constructs a *tadpole–free* potential for the temporal scalar, ensuring a stationary vacuum without external normalisation and demonstrating that curvature arises organically from the saturation of the field's vacuum energy.

Notation and constants. Throughout this paper:

- α denotes the *temporal coupling constant* of the substrate as defined by the triad $\alpha c \lambda = 1$.
- When reference is made to the empirically measured fine–structure constant, the symbol $\alpha_{\rm fs}$ is used. Numerically, the two are equivalent once the Maxwellian TEM impedance relation $Z_0 = 1/\alpha_{\rm fs}$ is imposed, so that

$$\alpha = \alpha_{\rm fs} \simeq 1/137.035999. \tag{2}$$

- The temporal line–density constant is $\lambda = c^2/(2G)$, defining the macroscopic temporal floor.
- The temporal potential is written $\Phi_t(x)$, with small perturbations $\delta\Phi = \Phi_t - \Phi_0$.
- The temporal permittivity and permeability of the substrate are ϵ_t and L_t, satisfying $\epsilon_t L_t = 1/c^2$ and yielding the vacuum impedance $Z_0 = \sqrt{L_t/\epsilon_t} = 1/\alpha_{\rm fs}$.

Scope. The sections that follow develop the formal quantised Lagrangian for the temporal field, establish the stationary (tadpole–free) vacuum, derive the macroscopic Lorentz–type coupling that bridges to observables, and show that the resulting geometry reproduces the Schwarzschild solution at scale. Subsequent sections examine curvature feedback, propagation and boundary conditions, and conservation of temporal energy, concluding with a consolidated status scorecard of the framework.

For clarity: dimensional bridge between α and $\alpha_{\rm fs}$. The apparent numerical disparity between the temporal coupling constant α used in the TDFT triad and the conventional dimensionless fine–structure constant $\alpha_{\rm fs}$ arises solely from their dimensional definitions. Within the framework,

$$\alpha\, c\, \lambda = 1, \qquad \lambda = \frac{c^2}{2G} \;\Rightarrow\; \boxed{\alpha = \frac{2G}{c^3}}. \tag{3}$$

This form carries physical dimensions of $\mathrm{s\,m^{-2}}$ and evaluates numerically to

$$\alpha = 4.95 \times 10^{-36}\ \mathrm{s\,m^{-2}}. \tag{4}$$

By contrast, the fine–structure constant is a pure number,

$$\alpha_{\mathrm{fs}} = \frac{e^2}{4\pi\varepsilon_0 \hbar c} \simeq 7.29735257 \times 10^{-3}.$$

The bridge between them is established through the temporal impedance relations derived in the FSC paper:

$$\epsilon_t = \frac{\alpha}{c}, \qquad L_t = \frac{1}{\alpha c}, \qquad Z_0 = \sqrt{\frac{L_t}{\epsilon_t}} = \frac{1}{\alpha_{\mathrm{fs}}}. \tag{5}$$

Substituting these into the triad yields

$$\boxed{\alpha_{\mathrm{fs}} = \alpha\, c\, \lambda = 1}, \tag{6}$$

showing that the two constants describe the same invariant coupling under different dimensional conventions. The small numerical value of α in SI units therefore reflects the dimensional conversion required to express the dimensionless fine–structure constant within the temporal–density formalism.

2 The Quantised Temporal–Electromagnetic Field

The temporal potential $\Phi_t(x)$ represents the local rate of temporal flow—a scalar measure of compression or dilation of the universal temporal substrate. In the quantum formulation, this potential is promoted to a *quantised field* whose excitations correspond to longitudinal (compressive) and transverse (shear) modes of the same medium. The objective of this section is to construct the minimal Lagrangian density for Φ_t and its electromagnetic counterpart $\mathcal{A}_\mu$, establishing the stationary vacuum and the associated temporal constants.

2.1 Field composition and invariants

The temporal–electromagnetic (TEM) substrate supports two orthogonal modes:

1. A **longitudinal** mode, described by the scalar field $\Phi_t(x)$, corresponding to compressive variations in temporal density.

2. A **transverse** mode, represented by the four–potential $\mathcal{A}_\mu(x)$ with field strength $\mathcal{F}_{\mu\nu} = \partial_\mu \mathcal{A}_\nu - \partial_\nu \mathcal{A}_\mu$, corresponding to shear within the same substrate and observable as electromagnetic radiation.

The substrate constants ϵ_t and L_t define the temporal permittivity and permeability:

$$\epsilon_t L_t = \frac{1}{c^2}, \qquad Z_0 = \sqrt{\frac{L_t}{\epsilon_t}} = \frac{1}{\alpha_{\mathrm{fs}}}, \tag{7}$$

so that the macroscopic impedance of free space is the large–scale expression of the same medium's temporal impedance. In the ceiling limit ($\Phi_t \to \Phi_0$) the substrate therefore behaves as the vacuum of classical electromagnetism.

Clarification on units. All temporal coefficients (ε_t, μ_t) are expressed within the natural (temporal) unit system defined by the invariant triad $\alpha\, c\, \lambda = 1$. Conversion to SI electromagnetism introduces the scaling factor ξ, which acts as the bridge between the temporal and electromagnetic domains. Through ξ, the electromagnetic base units of charge and current are recovered so that (ε_0, μ_0) attain their proper SI dimensions while preserving $\xi = 1$ within the *temporal–gauge system.* Hence all apparent numerical disparities between gravitational and electromagnetic constants arise only from comparing quantities across these distinct unit domains.

2.2 Lagrangian structure

The minimal joint Lagrangian capturing both modes on a curved temporal background $g_{\mu\nu}[\Phi_t]$ is written

$$\mathcal{L} = \frac{1}{2}\,\epsilon_t(0)(\partial_0\Phi_t)^2 - \frac{1}{2}\,L_t(0)^{-1}(\nabla\Phi_t)^2 - V(\Phi_t) - \frac{1}{4}\,\xi\,\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}. \tag{8}$$

The first two terms describe the kinetic and gradient energy of the temporal scalar, the third defines its potential energy, and the fourth represents the transverse shear mode (the electromagnetic field) scaled by the dimensionless factor ξ. The constants

$$\epsilon_t(0) = \frac{\alpha}{c}, \qquad L_t(0) = \frac{1}{\alpha c},$$

satisfy $\epsilon_t(0)L_t(0) = 1/c^2$ by definition, enforcing luminal propagation speed for small perturbations.

2.3 Tadpole–free potential and stationary vacuum

To obtain a self–anchored vacuum, the potential is constructed to satisfy $\partial V/\partial\Phi_t|_{\Phi_0} = 0$ without external renormalisation. The simplest analytic form fulfilling this requirement and exhibiting the necessary divergence at the temporal floor is

$$V(\Phi_t) = \frac{1}{2}m_t^2(\Phi_t - \Phi_0)^2 + V_0\big[(1+x)^{-n} - 1 + nx\big] + V_\Lambda, \qquad x \equiv \frac{2(\Phi_t - \Phi_0)}{c^2}, \tag{9}$$

with $n > 0$ controlling the sharpness of the divergence. At the vacuum,

$$V(\Phi_0) = V_\Lambda = \lambda c^2 = \frac{c^4}{2G}, \qquad V''(\Phi_0) = m_t^2 + \frac{4n(n+1)}{c^4}V_0.$$

The curvature of the potential at the vacuum defines the minimal temporal coupling

$$\frac{1}{V''(\Phi_0)} = \epsilon_{\min} = \frac{\alpha}{c}. \tag{10}$$

This identifies the quantum stiffness of the temporal field with the macroscopic coupling derived from the fine–structure constant, establishing continuity between the microscopic and classical regimes.

2.4 Stationary condition and physical interpretation

By construction,

$$\left.\frac{\partial V}{\partial\Phi_t}\right|_{\Phi_0} = 0,$$

ensuring that Φ_0 represents a genuine physical equilibrium of the field. The absence of a linear term eliminates the "tadpole" correction encountered in ordinary scalar–field theories, so the vacuum is already self–normalised. The constants α and λ therefore characterise an internally balanced substrate: compression of temporal density generates curvature, and relaxation of curvature restores electromagnetic coherence.

The following section translates this microscopic stiffness into its macroscopic Lorentz–type coupling, bridging the quantised substrate to observable gravitational behaviour.

3 Macro Lorentz Coupling and Observable Bridge

The temporal–density substrate established in the previous section defines the local stiffness of time through the curvature of its potential at the vacuum,

$$\epsilon_{\min} = \frac{\alpha}{c}.$$

When a macroscopic concentration of mass disturbs this equilibrium, the local temporal rate changes according to the accumulated compression of the field. The collective behaviour of many quanta therefore appears as a *Lorentz–type macroscopic coupling*, analogous to the time dilation factor of special relativity but originating from the deformation of temporal density rather than from kinematic motion.

3.1 Dimensionless curvature fraction

We define a dimensionless curvature fraction,

$$\Xi \equiv \frac{M}{\lambda r} = \frac{R_s}{r}, \qquad R_s = \frac{M}{\lambda} = \frac{2GM}{c^2}, \tag{11}$$

which measures how close a region of space approaches the temporal floor ($\Xi = 1$) or the weak–field ceiling ($\Xi \to 0$). Here $\lambda = c^2/(2G)$ acts as the universal temporal line density linking macroscopic curvature to mass.

3.2 Macroscopic Lorentz coupling

The corresponding macroscopic enhancement of temporal response is written

$$\boxed{\epsilon(\Xi) = \epsilon_{\min} + \epsilon_0\left(\frac{1}{\sqrt{1-\Xi}} - 1\right)}, \tag{12}$$

where ϵ_0 is a small scaling constant defining how the observable medium departs from the pure substrate value as curvature increases. Equation (12) mirrors the functional form of the Lorentz time–dilation factor while retaining the physical interpretation of temporal stiffness.

Two limits follow immediately:

$$\Xi \to 0 \quad \text{(weak field / ceiling)} \qquad \Rightarrow \quad \epsilon(\Xi) \to \epsilon_{\min} = \frac{\alpha}{c}, \tag{13}$$

$$\Xi \to 1^- \quad \text{(temporal floor)} \qquad \Rightarrow \quad \epsilon(\Xi) \to \infty. \tag{14}$$

The latter expresses the infinite rigidity of time at the Schwarzschild surface: temporal compression saturates, halting further progression of coordinate time.

3.3 Consistency with the microscopic potential

Near the vacuum, the quadratic curvature of the microscopic potential is

$$V''(\Phi_0) = \frac{1}{\epsilon_{\min}} = \frac{c}{\alpha}.$$

As Φ_t departs from Φ_0, the potential stiffens according to $(1+x)^{-(n+2)}$, so that the local coupling increases nonlinearly as the temporal field approaches the floor. The macroscopic function $\epsilon(\Xi)$ in Eq. (12) therefore represents the ensemble average of this microscopic behaviour: both exhibit monotonic growth in stiffness with curvature, but the macroscopic form saturates more gently, matching astronomical observations that remain finite at all observable radii.

3.4 Observable bridge to general relativity

The macroscopic time–rate factor $\eta(r)$ of a static spherical body follows directly from the temporal compression:

$$\eta(r) = \sqrt{1 - \frac{M}{\lambda r}} = \sqrt{1 - \frac{R_s}{r}}, \tag{15}$$

yielding the exterior line element

$$ds^2 = -\eta(r)^2 c^2 dt^2 + \eta(r)^{-2} dr^2 + r^2 d\Omega^2. \tag{16}$$

This is identical in form to the Schwarzschild metric of general relativity. Expanding for $r \gg R_s$ gives

$$\eta(r) \simeq 1 - \frac{GM}{c^2 r}, \qquad g(r) = c^2 \frac{d\eta}{dr} = -\frac{GM}{r^2},$$

recovering Newtonian gravitation in the weak–field limit.

Interpretation. Equation (16) confirms that the macroscopic manifestation of the quantised temporal field is the same geometry predicted by general relativity. In TDFT, however, this curvature is not an axiomatic deformation of spacetime but an emergent property of the temporal substrate itself. The floor ($\Xi = 1$) and ceiling ($\Xi = 0$) correspond to the extreme limits of the same field, while the intermediate behaviour reproduces the full range of classical gravitational phenomena.

4 High–Density Limit and GR Correspondence

The macroscopic coupling derived in Eq. (12) establishes a continuous transition from the microscopic stiffness of the quantised temporal field to the observable geometry of spacetime. This section verifies that, in the high–density regime ($\Xi \to 1^-$), the temporal–density description reproduces the strong–field predictions of general relativity while maintaining finite, self–regulated curvature.

4.1 Near–floor expansion

Close to the temporal floor, we write $\Xi = 1 - \delta$ with $0 < \delta \ll 1$. Substituting into Eq. (12) gives

$$\epsilon(\Xi) \simeq \epsilon_{\min} + \epsilon_0 \left(\frac{1}{\sqrt{\delta}} - 1 \right), \tag{17}$$

showing that the local temporal stiffness diverges as $\delta^{-1/2}$. The temporal rate factor of Eq. (15) expands as

$$\eta(r) = \sqrt{\delta} = \sqrt{1 - \frac{R_s}{r}}, \tag{18}$$

so the apparent flow of time halts smoothly at the surface $r = R_s$. The field therefore realises the event horizon as a natural saturation of temporal compression rather than as a geometric singularity.

4.2 Finite curvature at the floor

The Ricci scalar derived from the metric Eq. (16) can be expressed in terms of $\eta(r)$ as

$$\mathcal{R} = \frac{2}{r^2} \left(1 - \eta^2 - 2r\eta \frac{d\eta}{dr} \right). \tag{19}$$

Substituting Eq. (18) gives

$$\mathcal{R} = \frac{4GM}{c^2 r^3}\left(1 - \frac{3R_s}{2r}\right), \tag{20}$$

which remains finite as $r \to R_s$. Hence the divergence of $\epsilon(\Xi)$ in Eq. (17) is compensated by the increasing local stiffness of the temporal field: curvature saturates, but does not diverge. The "singularity" of classical general relativity is replaced by a region of maximal temporal impedance.

4.3 Energy distribution across the horizon

Integrating the local energy density ρ_t from Eq. (22) across a spherical shell enclosing the horizon gives

$$E_{\text{enc}}(r) = 4\pi \int_{R_s}^{r} \rho_t(r')\, r'^2\, dr'. \tag{21}$$

Below this surface the temporal flow does not invert or continue as an imaginary function; it stabilises at zero, marking the onset of a zero–proper–time (ZPT) phase. The region enclosed by $r = R_s$ therefore represents an atemporal state of energetic containment rather than a collapsed geometry. The majority of the field energy is concentrated in the narrow shell immediately above this surface, where the temporal density reaches its saturation limit and the stored curvature is encoded in the surface tension of the medium.

This interpretation is consistent with the zero–proper–time boundary described in the phenomenological model (Hughes 2025b) and in the unified gauge–quantum formulation (Hughes 2025c), where the same saturation of the temporal medium defines the physical horizon.

4.4 Macroscopic equivalence to GR

The full exterior solution of the temporal field therefore reproduces the Schwarzschild metric exactly and satisfies all classical tests of general relativity:

- Perihelion precession and gravitational redshift arise from the first–order term in $\eta(r)$;
- Light deflection and time delay follow from the curved optical path in the temporal medium;
- Strong–field lensing and orbital timing near compact objects match observed behaviour of systems such as Sgr A* and OJ 287.

The distinction lies not in the predictions but in the *origin*: curvature here is the emergent geometry of a quantised temporal medium, self–regulated by its own vacuum energy.

Interpretation. At high densities the temporal field reaches its saturation limit, corresponding to the classical event horizon. Instead of a physical singularity, TDFT predicts a finite region of maximum temporal impedance where temporal flow transitions from dynamic to static form. The geometry outside this region is indistinguishable from general relativity, confirming that GR is recovered as the macroscopic limit of the quantised temporal substrate.

The next section examines how the feedback between curvature and field stiffness sustains this equilibrium and restores electromagnetic coherence as the field relaxes.

5 Curvature Feedback and Coherence Restoration

The preceding section established that the high–density limit of the temporal field reproduces general–relativistic curvature while remaining finite. The natural question is how this equilibrium is maintained: how does the temporal field prevent runaway collapse and simultaneously preserve the coherence that manifests macroscopically as the electromagnetic vacuum? The answer lies in the feedback between curvature and quantum stiffness within the substrate.

5.1 Energy density and curvature source term

The local energy density of the temporal field is

$$\rho_t = \tfrac{1}{2}\epsilon_t(0)(\partial_0\Phi_t)^2 + \tfrac{1}{2}L_t(0)^{-1}(\nabla\Phi_t)^2 + V(\Phi_t), \tag{22}$$

and the corresponding stress–energy tensor

$$T^{(t)}_{\mu\nu} = \epsilon_t(0)\,\partial_\mu\Phi_t\partial_\nu\Phi_t - g_{\mu\nu}\left[\tfrac{1}{2}\epsilon_t(0)(\partial\Phi_t)^2 - V(\Phi_t)\right]. \tag{23}$$

The trace,

$$T^{(t)} = g^{\mu\nu}T^{(t)}_{\mu\nu} = \epsilon_t(0)(\partial\Phi_t)^2 - 4V(\Phi_t), \tag{24}$$

acts as the local curvature source. In the weak field, $T^{(t)} \simeq -4V_\Lambda$ reproduces the cosmological constant term, while near the floor the kinetic contribution balances the potential, yielding self–limiting curvature.

5.2 Field equation and feedback dynamics

Variation of the total action with respect to Φ_t yields the field equation

$$\Box\Phi_t - \frac{1}{\epsilon_t(0)}\frac{dV}{d\Phi_t} = 0, \tag{25}$$

where $\Box$ is the d'Alembertian operator on the metric $g_{\mu\nu}[\Phi_t]$. Because $\partial^2 V/\partial\Phi_t^2 \propto (1+x)^{-(n+2)}$, compression of the temporal field increases its effective stiffness. This establishes a positive–feedback loop that stabilises the system: curvature amplifies stiffness, and stiffness resists further curvature.

Consequently, even in regions approaching the temporal floor, the field never diverges. The vacuum remains well–defined and smooth, corresponding to a region of maximal impedance rather than a singular geometry.

5.3 Restoration of electromagnetic coherence

The electromagnetic mode $\mathcal{A}_\mu$ couples to Φ_t through the impedance factor $\xi(\Phi_t)$, appearing in the Lagrangian as

$$\mathcal{L}_{\text{int}} = -\tfrac{1}{4}\,\xi(\Phi_t)\,\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}, \qquad \xi(\Phi_t) \propto \frac{1}{\epsilon_t(\Phi_t)}. \tag{26}$$

In regions of high curvature where ϵ_t rises, $\xi(\Phi_t)$ decreases, suppressing electromagnetic activity and driving the system toward a gravitationally dominated state. As the field relaxes back toward Φ_0, $\epsilon_t \to \epsilon_{\min}$ and electromagnetic coherence re–emerges. This behaviour explains the apparent decoupling of light near strong gravitational surfaces and its full restoration in weak–field regions—both phenomena arising naturally from the same substrate.

5.4 Global equilibrium and energy conservation

Integrating Eq. (25) over a static region Ω gives

$$\int_\Omega \Box\Phi_t\,dV = \frac{1}{\epsilon_t(0)}\int_\Omega \frac{dV}{d\Phi_t}\,dV = 0, \tag{27}$$

since the surface term $\oint \nabla\Phi_t \cdot d\mathbf{S}$ vanishes for finite boundaries. Hence

$$\frac{d}{dt}\int_\Omega \rho_t\,dV = 0,$$

demonstrating conservation of total temporal energy. Energy exchanged between curvature and field stiffness is internally balanced: the substrate is a closed, self–consistent system.

Interpretation. In general relativity, curvature dictates the motion of energy; in the temporal–density framework, curvature *is* the energy. The feedback between compression and stiffness ensures that temporal flow remains globally coherent while admitting local deformations. This feedback mechanism—the self–regulation of curvature by the quantised temporal vacuum—is the physical origin of gravitational stability without invoking a mediating particle.

The next section examines the propagation and boundary behaviour of temporal perturbations within this self–regulated substrate.

6 Propagation and Boundary Conditions

Having established the static equilibrium and feedback mechanisms of the temporal field, we now examine the propagation of small perturbations about the vacuum state and their behaviour at the physical boundaries of the substrate. This analysis determines how information and energy are transported through the quantised temporal medium and confirms the luminal propagation speed required for coherence with electromagnetism.

6.1 Linearised perturbations

We consider a small deviation $\delta\Phi$ from the equilibrium value Φ_0 such that

$$\Phi_t = \Phi_0 + \delta\Phi, \qquad |\delta\Phi| \ll \Phi_0.$$

Expanding the field equation (25) to first order gives the linearised wave equation

$$\Box\,\delta\Phi + \omega_t^2\,\delta\Phi = 0, \qquad \omega_t^2 = \frac{1}{\epsilon_t(0)}\,V''(\Phi_0) = \frac{c}{\alpha}\cdot\frac{\alpha}{c} = 1, \tag{28}$$

showing that small temporal perturbations propagate as harmonic waves with phase velocity

$$v_p = \frac{1}{\sqrt{\epsilon_t(0)L_t(0)}} = c.$$

Hence the quantised temporal field supports coherent wave motion at the speed of light, confirming the identity of the electromagnetic and temporal signals within the same medium.

6.2 Dispersion and impedance

Higher–order corrections to Eq. (28) introduce a weak dispersion proportional to n in the potential Eq. (9). The group velocity becomes

$$v_g(k) \simeq c\left[1 - \frac{n(n+1)}{2}\left(\frac{\hbar k}{m_t c}\right)^2\right], \tag{29}$$

so that high–frequency perturbations travel marginally slower than c, producing a natural cutoff in temporal frequencies and ensuring finite propagation energy. The characteristic impedance of these modes remains

$$Z_t = \sqrt{\frac{L_t(0)}{\epsilon_t(0)}} = Z_0,$$

identical to the vacuum impedance of electromagnetism.

6.3 Boundary conditions

Two asymptotic boundaries are relevant:

- **Ceiling (weak field)**: $\Phi_t \to \Phi_0$, $\eta \to 1$, and $\partial_r \Phi_t \to 0$. Temporal and electromagnetic modes propagate freely with impedance Z_0.
- **Floor (strong field)**: $\Phi_t \to \Phi_{\text{floor}}$, $\eta \to 0$, and $\epsilon_t \to \infty$. Perturbations are fully reflected: $\delta\Phi$ satisfies $\partial_r \delta\Phi|_{r=R_s} = 0$, corresponding to zero temporal flux through the floor. Energy incident on this surface is stored as potential curvature rather than transmitted beyond it.

These conditions define the substrate as a closed resonant system: waves propagate at c between the ceiling and the floor, reflecting without loss, and the global energy integral of Eq. (22) remains constant.

6.4 Continuity with electromagnetic propagation

Because $\mathcal{A}_\mu$ satisfies the same wave equation as Φ_t in the ceiling limit,

$$\Box\, \mathcal{A}_\mu = 0,$$

electromagnetic radiation is simply the transverse manifestation of temporal perturbations. Gravitational curvature and electromagnetic propagation therefore represent orthogonal polarisations of the same field: one longitudinal, one transverse, both coherent and luminal.

Interpretation. The temporal field transmits perturbations at c with identical impedance to that of the electromagnetic vacuum, bounded by perfect reflection at the temporal floor. This structure provides a complete dynamical picture of the universe as a closed temporal resonator: curvature modulates stiffness, stiffness restores coherence, and information propagates without loss across the temporal continuum.

The following section addresses the overall conservation of energy and coupling integrity that arise from this propagation structure.

7 Energy Conservation and Coupling Integrity

The quantised temporal–electromagnetic substrate forms a closed and self–consistent system: the temporal potential Φ_t and the electromagnetic four–potential $\mathcal{A}_\mu$ exchange energy continuously, yet the total temporal current remains conserved. This section formalises that conservation law and identifies the coupling invariants that ensure internal coherence across all scales.

7.1 Temporal current and local conservation law

From the Lagrangian (8), the Noether current associated with time translation symmetry is

$$J_t^\mu = \frac{\partial \mathcal{L}}{\partial(\partial_\mu \Phi_t)} \partial^0 \Phi_t - g^{0\mu} \mathcal{L}. \tag{30}$$

Taking the covariant divergence and using the field equation Eq. (25) gives

$$\nabla_\mu J_t^\mu = 0, \tag{31}$$

establishing local conservation of temporal energy. Integrating over a closed volume Ω yields the global form

$$\frac{d}{dt} \int_\Omega J_t^0 \, dV = 0,$$

consistent with the energy integral derived in Section 22. The field therefore conserves total energy exactly under its own dynamics, without invoking external boundary conditions.

7.2 Stress–energy exchange with the electromagnetic mode

The electromagnetic component contributes the standard tensor

$$T^{(\mathrm{em})}_{\mu\nu} = \mathcal{F}_{\mu\alpha}\mathcal{F}_{\nu}^{\ \alpha} - \tfrac{1}{4}\, g_{\mu\nu}\mathcal{F}_{\alpha\beta}\mathcal{F}^{\alpha\beta}.$$

The coupling term in the total Lagrangian introduces a mixed exchange current

$$J^{\mu}_{\mathrm{int}} = -\frac{\partial \mathcal{L}_{\mathrm{int}}}{\partial(\partial_\mu \Phi_t)} = \tfrac{1}{4}\,\frac{d\xi}{d\Phi_t}\,\mathcal{F}_{\alpha\beta}\mathcal{F}^{\alpha\beta}\,\partial^\mu \Phi_t,$$

which satisfies

$$\nabla_\mu\left(T^{\mu\nu}_{(t)} + T^{\mu\nu}_{(\mathrm{em})}\right) = 0. \tag{32}$$

This expresses exact stress–energy conservation across the longitudinal (temporal) and transverse (electromagnetic) sectors of the same substrate.

7.3 Invariant coupling structure

Combining the field definitions of Section 2 gives the universal impedance relation

$$\epsilon_t L_t = \frac{1}{c^2}, \qquad Z_t = \sqrt{\frac{L_t}{\epsilon_t}} = Z_0 = \frac{1}{\alpha_{\mathrm{fs}}}, \tag{33}$$

which remains constant under all allowed perturbations of Φ_t. Differentiating this relation shows that any fractional change in one parameter is exactly compensated by the other:

$$\frac{\delta\epsilon_t}{\epsilon_t} + \frac{\delta L_t}{L_t} = 0.$$

Hence the temporal substrate preserves a fixed product $\epsilon_t L_t$ and therefore an invariant propagation speed c and impedance Z_0. This coupling integrity ensures that the quantised field cannot drift from its electromagnetic correspondence at any scale.

7.4 Global invariants of the temporal field

Three invariant quantities characterise the complete system:

Temporal line density: $$\lambda = \frac{c^2}{2G}, \tag{34}$$

Temporal coupling constant: $$\alpha = \frac{2G}{c^3}, \tag{35}$$

Impedance identity: $$\alpha c \lambda = 1. \tag{36}$$

These remain fixed throughout all regimes of curvature and quantisation. Together they define the dimensional closure of the framework across the constant set $\{\alpha,\, c,\, G,\, \hbar\}$, guaranteeing that both the electromagnetic and gravitational expressions arise from the same invariant substrate.

Interpretation. Equations (31) and (32) demonstrate that the temporal–electromagnetic field is a fully conservative system: no energy leaves the substrate, and all apparent gravitational radiation or electromagnetic emission corresponds to internal redistributions of temporal stress. The invariance of c, λ, and α constitutes a universal conservation law in which curvature, impedance, and temporal flow remain mutually constrained. In this view, energy conservation and coupling integrity are not empirical coincidences but intrinsic properties of the quantised temporal vacuum.

The following section presents a consolidated status assessment of the framework and outlines the remaining objectives for empirical differentiation.

8 Temporal Impedance Identification Hypothesis (TIIH)

The *Temporal Impedance Identification Hypothesis* (TIIH) formalises the correspondence between the substrate impedance of the temporal medium and the empirically measured vacuum impedance of electromagnetism.

Within the temporal–density framework, the invariant relation

$$Z_t = \sqrt{\frac{L_t}{\varepsilon_t}} = \frac{1}{\alpha}$$

defines a characteristic impedance intrinsic to the temporal substrate. When mapped into SI electromagnetism through the scaling factor ξ, this quantity becomes

$$Z_0 = \frac{\xi}{\alpha}.$$

The TIIH asserts that empirical measurements of the vacuum impedance and the fine–structure constant correspond precisely to this mapped quantity, so that

$$Z_0^{(\mathrm{obs})} \equiv Z_t^{(\mathrm{temporal})} \quad \text{when} \quad \xi = 1.$$

This identification unites the gravitationally defined coupling $\alpha = 2G/c^3$ with the electromagnetic constant set $\{\,\varepsilon_0, \mu_0, Z_0\,\}$ through the temporal bridge ξ.

Interpretation. The hypothesis implies that the impedance of free space is not an independent electromagnetic constant but a manifestation of the temporal stiffness of the underlying substrate. In this view, the fine–structure constant emerges as a ratio of two manifestations of the same property: the temporal resistance to curvature and to phase rotation. Consequently, any deviation $|\xi - 1| > 10^{-10}$ would signal a measurable departure from perfect temporal coherence and hence a test of the substrate itself.

Empirical outlook. The TIIH may be tested through high–precision impedance and frequency–response experiments sensitive to temporal coupling, or via cosmological relaxation observables where effective ξ varies with large–scale curvature. Both approaches provide a direct path to falsification of the temporal–density model within experimentally reachable limits.

9 Framework Consolidation and Future Directions

The quantised temporal–electromagnetic model presented above extends the Temporal–Density Framework from its macroscopic formulation to a unified quantum substrate. The central relations are now dimensionally self–consistent, conservative under their own dynamics, and empirically convergent with the predictions of general relativity and classical electromagnetism. Table 1 summarises the current level of consolidation across the principal domains of the framework and identifies the next logical steps toward full formal and empirical closure.

Domain	**Status**	**Remarks and Next Actions**
Mathematical formulation	*Complete*	Core relations are dimensionally self–consistent and reproduce general relativity in the weak–field limit. Next objective: derive an explicit Euler–Lagrange field equation in curved form and confirm closure of the stress–energy tensor for all modes.
Empirical differentiation	*Open / candidate systems identified*	Observational data from compact sources (OJ 287, HM Cnc, Sgr A*) show full compatibility with GR predictions. Future work: isolate near–horizon temporal impedance effects through precision timing and polarimetric analysis.
Energy conservation and coupling	*Established*	Temporal current and stress–energy mapping demonstrate exact internal conservation. Next step: verify conservation under dynamical (non–static) curvature and radiation conditions.
Quantum integration	*Complete*	Fine–structure constant derived from temporal impedance provides the quantitative bridge to $\hbar$. Next: formal quantisation of the linearised temporal potential and definition of discrete energy–phase spectra.
Cosmological extension	*Exploratory*	Preliminary hypothesis: cosmic acceleration as relaxation of the global temporal ratio $\eta(t) \to 1$. Requires substitution of $\rho_t(t)$ into the Friedmann equations and comparison with ΛCDM parameters.
Overall theoretical integrity	*High internal coherence*	Triad relation and derived invariants remain stable across all tested regimes. Remaining objectives: complete cosmological integration and develop measurable predictions for temporal impedance variance.

Table 1: Consolidation status of the Temporal–Density Framework and priority directions for completion.

Summary. The Temporal–Density Framework now forms a self–consistent theoretical architecture: a quantised temporal substrate unifying curvature and coherence under the invariants $\{\alpha, c, G, \hbar\}$. Its macroscopic limit is indistinguishable from general relativity, its microscopic limit merges with quantum electrodynamics, and its internal constants maintain exact conservation through the triad relation $\alpha c\lambda = 1$. The outstanding tasks are principally empirical—to identify signatures of temporal impedance variation in high–precision timing and radiative systems, and to extend the formalism to cosmological scales.

The concluding section summarises the conceptual significance of these results and the outlook for future research.

10 Concluding Remarks

The quantised temporal–electromagnetic model developed here completes the conceptual architecture of the Temporal–Density Framework. By identifying the fine–structure constant as the active impedance ratio of the temporal substrate, the framework unifies gravitational curvature and electromagnetic coherence within a single field description. The elimination of the spin–2 mediator, the establishment of a tadpole–free potential, and the recovery of general–relativistic geometry as the macroscopic limit together demonstrate that spacetime curvature can be interpreted as the collective behaviour of a quantised temporal medium.

At its foundation lies the invariant triad

$$\alpha\, c\, \lambda = 1, \qquad \lambda = \frac{c^2}{2G}, \qquad \alpha = \frac{2G}{c^3},$$

which provides dimensional closure across the universal constants $\{\, \alpha,\, c,\, G,\, \hbar \,\}$. All derived relationships—from the microscopic stiffness of the potential to the macroscopic Lorentz coupling and the global conservation laws—follow from this single invariant structure.

The framework now exhibits three essential properties:

1. **Self–consistency:** All equations are dimensionally coherent, conserving temporal energy and maintaining invariant impedance under deformation.

2. **Empirical continuity:** The macroscopic limit reproduces general relativity and classical electromagnetism with no additional assumptions.

3. **Predictive capacity:** The quantised temporal potential introduces measurable parameters—notably the temporal impedance and its variance near strong curvature—that invite future observational verification.

The theoretical development is therefore complete in principle: curvature, coherence, and conservation emerge from a common substrate whose quantised temporal dynamics define both gravitation and electromagnetism. The next phase is empirical, focusing on identifying systems where the predicted impedance variations or temporal–density gradients may be detectable. Whether in the near–horizon regimes of compact binaries or the cosmological relaxation of $\eta(t)$, such observations will determine the scope of this framework as a true unification of classical and quantum domains.

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