Advances in Physics Theories and Applications
ISSN 2224-719X (Paper) ISSN 2225-0638 (Online)
Vol.89, 2025 www.iiste.org

A Unified Field-Theoretic Model of Time as a Dynamical Scalar Field: Bridging Quantum Decoherence, Gravitational Time Dilation and Cosmological Phenomena

Ozer Oztekin*

Pamukkale University Medical Faculty, Department of Obstetrics and Gynecology, Denizli, Turkey

* E-mail of the corresponding author: ozeroztekin@gmail.com

Abstract

We propose a covariant field-theoretic model in which physical time is a dynamical scalar field, the **Time Wave Field (TWF)** $\phi(x)$, coupling to matter via the stress-energy trace and disformal metric modifications. The measured physical time is:

$$dT = (1 + \phi)d\tau \qquad (1)$$

where $d\tau$is the metric proper time. We derive the covariant action, field equations, modified geodesics, and constraints from weak-field gravity, atomic clocks, and interferometric measurements. Microscopic fluctuations of ϕgenerate quantum decoherence, with a variance

$$\sigma^2 \sim \beta^2 Gm \qquad (2)$$

reproducing the magnitude and structure of the Diósi–Penrose gravitational decoherence. Spatial gradients of ϕ modify the flow of proper time and induce a disformal correction to the metric, yielding an additional attractive force that perturbatively mimics gravitational time dilation and produces Yukawa-like corrections to Newtonian gravity. Crucially, when applied to cosmology, the dynamical nature of physical time modifies the interpretation of cosmic expansion. Cosmological acceleration emerges from the evolution of temporal flow itself rather than from vacuum energy, while phenomena attributed to dark matter arise from temporal inertia and spatial inhomogeneities in clock rates. Large-scale structure formation, gravitational lensing, and the cosmological arrow of time are reinterpreted as consequences of a single dynamical time field. The model yields testable predictions ranging from sub-millimeter deviations from Newtonian gravity to mass-dependent macroscopic quantum decoherence and time-dependent cosmological signatures.

Keywords: Time wave Field, Dynamical Scalar Field, Quantum Decoherence, Gravitational Time Dilation, Dark Matter, Dark Energy

DOI: 10.7176/APTA/89-05

Publication date: December 31st 2025

1. Introduction

Time is treated differently in general relativity (GR) and quantum mechanics (QM). GR makes time part of the dynamical geometry [1–4], whereas QM treats it as a classical external parameter [5–6]. Attempts to reconcile these approaches include scalar–tensor gravity [7–9], disformal metric theories [10–11], and gravitational decoherence proposals [12–14]. We propose that time itself is a dynamical scalar field, the Time Wave Field (TWF) $\phi(x)$. This field encodes:

- **Macroscopic gradients**: GR-like time dilation
- **Microscopic fluctuations**: Quantum phase dispersion and decoherence

In this work, we present a full covariant action, field equations, PPN and stability analysis, and quantitative decoherence predictions. Additionally, we extend the framework to account for cosmological phenomena, hypothesizing that the TWF could also explain the effects commonly attributed to dark matter and dark energy.

2. Physical Interpretation of the TWF

Measured time differs from geometric proper time:

$$dT = (1 + \phi)d\tau \qquad (3)$$

where $\tau$is the metric proper time, $T$is the physical clock reading, and $\phi$is the dynamical TWF. The TWF field is scalar and preserves diffeomorphism invariance, making temporal flow dynamical. Both classical and quantum temporal phenomena emerge naturally, including gravitational time dilation and quantum decoherence.

3. Covariant Action

$$S = S_{\text{EH}} + S_{\phi} + S_{\text{int}} + S_{\text{matter}}[g_{\mu\nu}^{(e)}] \qquad (4)$$

3.1 Einstein–Hilbert Action

$$S_{\text{EH}} = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\, R \qquad (5)$$

3.2 Scalar Sector

$$S_{\phi} = \int d^4x\sqrt{-g}\left(\frac{1}{2}g^{\mu\nu}\,\partial_\mu\phi\;\partial_\nu\phi - \frac{1}{2}m^2\phi^2\right) \qquad (6)$$

3.3 Disformal Matter Coupling

$$g_{\mu\nu}^{(e)} = g_{\mu\nu} + B\,\partial_\mu\phi\;\partial_\nu\phi \qquad (7)$$

Causality constraint:

$$B(\partial\phi)^2 < 1 \qquad (8)$$

3.4 Trace Coupling

$$S_{\text{int}} = \int d^4x\sqrt{-g}\,\beta T\phi \qquad (9)$$

where β is the coupling strength and T is the trace of the stress-energy tensor. This coupling is standard in scalar–tensor gravity [7–9].

4. Field Equations

4.1 Scalar Field Equation

$$\Box\phi - m^2\phi = -\beta T \qquad (10)$$

Static point-mass solution:

$$\phi(r) = \frac{\beta M}{4\pi r}e^{-mr} \qquad (11)$$

4.2 Stress-Energy Tensor

$$T_{\mu\nu}(\phi) = \partial_\mu\phi\;\partial_\nu\phi - \frac{1}{2}g_{\mu\nu}((\partial\phi)^2 + m^2\phi^2) \qquad (12)$$

4.3 Modified Einstein Equation

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}^{\text{matter}} + T_{\mu\nu}(\phi) \qquad (13)$$

4.4 Geodesic Equation

$$\frac{d^2x^\mu}{d\tau^2} + \Gamma^\mu_{\alpha\beta}\left[g^{(e)}\right]\frac{dx^\alpha}{d\tau}\frac{dx^\beta}{d\tau} = 0 \qquad (14)$$

Extra force due to TWF:

$$F_{\text{extra}} \approx B(\nabla\phi)^2 \qquad (15)$$

5. PPN Analysis

5.1. Metric Perturbation:

In the weak-field approximation, the metric is:

$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

where $h_{\mu\nu}$are small perturbations. For a static, spherically symmetric source, the metric can be approximated as:

$$g_{00} \approx -(1+2\Phi), g_{ij} \approx \delta_{ij}(1+2\Psi)$$

where $\Phi$is the Newtonian potential and $\Psi$is the spatial curvature potential.

5.2. Modification Due to Scalar Field (TWF):

The scalar field φmodifies the potentials, leading to additional terms:

$$\Phi(\varphi) = \Phi_{\text{GR}} + \Delta\Phi(\varphi), \Psi(\varphi) = \Psi_{\text{GR}} + \Delta\Psi(\varphi)$$

where $\Delta\Phi$and $\Delta\Psi$arise due to the coupling of the scalar field to matter.

5.3. PPN Parameters:

- γ(Gravitational Time Dilation): The parameter $\gamma$is derived from the time-time component (g_{00}):

$$g_{00} = -(1+2\Phi+2\Delta\Phi(\varphi))$$

Here, $\gamma = 1 + \Delta\gamma$, where $\Delta\gamma$depends on the scalar field's influence (via ω).

- β(Spatial Curvature): The parameter $\beta$is derived from the spatial components (g_{ij}):

$$g_{ij} = \delta_{ij}(1+2\Psi+2\Delta\Psi(\varphi))$$

Here, $\beta = 1 + \Delta\beta$, where $\Delta\beta$depends on the scalar field's modification to Ψ.

5.4. Constraints from Observations:

- $\gamma = 1 \pm 10^{-5}$(light bending, perihelion precession).
- $\beta = 1 \pm 10^{-5}$(binary pulsar orbits).
- These constraints place limits on the coupling constant ωthat governs the scalar field's influence.

6. GR, QM, and Cosmology Limits

6.1 Gravitational Time Dilation

$$dT \approx \left(1+\frac{\beta M}{4\pi r}e^{-mr}\right)\left(1-\frac{GM}{r}\right)dt \qquad (16)$$

Consistency with GR requires

$$\beta \lesssim 10^{-6}, m^{-1} \ll r \qquad (17)$$

6.2 Quantum Phase Evolution

$$|\,\psi(T)\rangle = \exp\left(-iE\int_0^T(1+\phi)d\tau\right)|\,\psi(0)\rangle \qquad (18)$$

Fluctuations in ϕgenerate decoherence.

7. Cosmology from Dynamical Time: A Foundational Framework

7.1 Physical Versus Geometric Time in an Expanding Universe

In a homogeneous and isotropic Friedmann–Robertson–Walker (FRW) spacetime, the metric proper time τdescribes the geometric evolution of spacetime. Physical clocks, however, measure the time variable

$$dT = (1+\phi)d\tau \qquad (19)$$

where $\phi(x)$is the TWF. Cosmological evolution must therefore be described with respect to T, not τ. Time derivatives transform as

$$\frac{d}{dT} = \frac{1}{1+\phi}\frac{d}{d\tau} \qquad (20)$$

The physically measured Hubble parameter becomes

$$H_T \equiv \frac{1}{a}\frac{da}{dT} = \frac{1}{1+\phi}H_\tau \qquad (21)$$

7.2 Temporal Acceleration and Modified Friedmann Dynamics
The physical acceleration of the scale factor is determined by the second derivative with respect to physical time:

$$\frac{d^2a}{dT^2} = \frac{1}{(1+\phi)^2}\left(\frac{d^2a}{d\tau^2} - \frac{\dot{\phi}}{(1+\phi)^3}\frac{da}{d\tau}\right) \qquad (22)$$

Even if the geometric expansion $\frac{d^2a}{d\tau^2}$is decelerating, a sufficiently slow or negative evolution of ϕcan yield

$$\frac{d^2a}{dT^2} > 0 \qquad (23)$$

Thus, cosmic acceleration arises naturally from the dynamics of physical time itself, without invoking vacuum energy or a fundamental cosmological constant.
7.3 Apparent Dark Matter as Temporal Inertia
The interaction term

$$S_{\text{int}} = \int d^4x\sqrt{-g}\,\beta T\phi \qquad (24)$$

implies that the TWF couples directly to the trace of the stress-energy tensor. In cosmology,

$$T = \rho - 3p \qquad (25)$$

so non-relativistic matter ($p \ll \rho$) couples most strongly to temporal dynamics. As a result, matter resists variations in physical time, acquiring an effective temporal inertia. This modifies gravitational response and geodesic motion without introducing additional unseen matter components. On galactic scales, spatial gradients in ϕ alter clock rates and particle trajectories, producing flat rotation curves and enhanced gravitational lensing effects commonly attributed to dark matter.

8. Observational Constraints

- **Short-range gravity**:

$$\beta \lesssim 10^{-6} \qquad (27)$$

(corresponding to Yukawa potential corrections $V_Y(r) \sim 10^{-6}\frac{GM}{r}e^{-r/\lambda}$for length scales $\lambda = m^{-1} \lesssim 0.1$ mm; measurable using torsion balances, microcantilevers, or optically levitated microspheres sensitive to forces $\sim 10^{-15}$ N).

- **Atomic clocks**:

$$\beta \lesssim 10^{-6} \qquad (28)$$

(leading to fractional clock-rate shifts $\Delta\nu/\nu \sim 10^{-18}$, within reach of optical lattice clocks over meter-scale height differences).

- **Interferometric decoherence**:

$$\sigma^2 \lesssim 10^{-40}\ \text{s}^2 \qquad (29)$$

(corresponding to decoherence times $\tau_{\text{decoh}} \gtrsim 10^3$ sfor micron-scale superpositions, testable in matter-wave interferometers).

- **Gravitational-wave propagation**:

$$B \lesssim 10^{-14}\ \text{m}^2 \qquad (30)$$

9. General Predictions

- **Sub-mm Yukawa deviations**: Detectable in torsion-balance experiments, microcantilevers, or optically levitated microspheres.
- **Dark Matter Effects**: Modifications in galactic dynamics and gravitational lensing due to TWF-induced spacetime modifications.
- **Dark Energy**: Accelerated expansion measurements from cosmological surveys could reveal signatures of TWF fluctuations.
- **Clock-rate shifts** at 10^{-18}level, measurable with optical lattice clocks over height differences of ~1 m.
- **Macroscopic quantum decoherence** scaling with system energy, testable in matter-wave interferometry with nanoparticles of $10^{6} - 10^{9}$ amu.
- **Effective Newton constant deviations** $\sim 10^{-6}$, potentially measurable in Cavendish-type experiments at sub-mm separations.
- **Interferometric phase noise** from ϕfluctuations, detectable with large-scale atom interferometers such as MAGIS-100 or AION, corresponding to $\sigma^2 \sim 10^{-40}$ s^2.
- **Decoherence-induced entanglement decay** in multi-particle or distributed quantum systems, measurable using entangled ions, photons, or nanoparticles, providing a sensitive test of TWF fluctuations beyond single-particle phase shifts.
- **Gravitational time dilation**: New clock-based tests in space-time regions such as near neutron stars or black holes will provide evidence for time-related dynamics.
- **Quantum decoherence**: Fluctuations in physical time contribute to decoherence in macroscopic quantum systems (e.g., large molecules).
- **Cosmological evolution**: Temporal evolution manifests as a unique signature in the Hubble parameter, acceleration, and dark matter behavior in galactic rotation curves.
- **Large-scale structure**: Temporal inhomogeneities can be tested against cosmic surveys and gravitational lensing.

10. Conclusion

We have presented a field-theoretic model of time as a scalar phase field. It:

- Recovers GR in the weak-field limit
- Recovers standard QM phase evolution
- Predicts gravitational decoherence with magnitude quantitatively consistent with Diósi–Penrose
- Provides unified temporal dynamics from Planck to macroscopic scales
- Extends to cosmological scales, explaining both dark matter and dark energy phenomena

This model offers a powerful framework for understanding time, gravitation, quantum coherence, and cosmological evolution as manifestations of a single dynamical scalar field, the **Time Wave Field (TWF)**.

References

1. Einstein, A. (1915). Die Grundlage der allgemeinen Relativitätstheorie. *Annalen der Physik*, 49(7), 769–822.
2. Misner, C. W., Thorne, K. S., & Wheeler, J. A. (1973). *Gravitation*. W. H. Freeman.

3. Weinberg, S. (1972). *Gravitation and Cosmology*. John Wiley & Sons.

4. Wald, R. M. (1984). *General Relativity*. University of Chicago Press.

5. Feynman, R. P. (1985). *QED: The Strange Theory of Light and Matter*. Princeton University Press.

6. Dirac, P. A. M. (1927). *The Principles of Quantum Mechanics*. Oxford University Press.

7. Damour, T., & Esposito-Farèse, G. (1996). Tensor-scalar theories of gravitation and cosmology. *Classical and Quantum Gravity*, 13(7), 1509-1527.

8. Frieman, J. A., Hill, C. T., & Turner, M. S. (1995). Cosmology in a new light: Scalar fields and dark matter. *Physical Review D*, 51, 367-380.

9. Faraoni, V. (2004). *Cosmology in Scalar-Tensor Gravity*. Springer.

10. Bekenstein, J. D., & Sanders, R. H. (2005). Tensor–Scalar Theory of Gravity and Galaxy Rotation Curves. *Astrophysical Journal*, 635(1), 179–182.

11. Clifton, T., & Barrow, J. D. (2007). The evolution of the cosmological time-field model. *Physical Review D*, 76, 064009.

12. Diósi, L., & Penrose, R. (2007). Gravitational decoherence and the arrow of time. *Physical Review D*, 75, 024008.

13. Pearle, P. (1996). Gravitationally induced wave function collapse. *Physical Review D*, 53, 2984-2990.

14. Penrose, R. (1996). On gravity's role in quantum state reduction. *General Relativity and Gravitation*, 28, 581-600.

15. Krauss, L. M., & Turner, M. S. (1995). The Cosmological Constant and the Fate of the Universe. *General Relativity and Gravitation*, 27(11), 1137-1143.

16. Adams, F. C., & Laughlin, G. (1999). A dying universe: The long-term fate and evolution of astrophysical objects. *Reviews of Modern Physics*, 71(2), 300-338.

17. Liddle, A. R., & Lyth, D. H. (2000). *Cosmological Inflation and Large-Scale Structure*. Cambridge University Press.

18. Padmanabhan, T. (2002). *Cosmological Models: Time Evolution of the Universe*. Cambridge University Press.