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The Essence and Nature of the Speed of Light: A Fundamental Constant Emerging from Vacuum Structure

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Abstract

The speed of light, long regarded as a fundamental and immutable constant of nature, is reexamined in this work through the lens of a novel framework that treats the vacuum not as empty space but as a structured superfluid medium—referred to as the Omniom. Drawing from classical hydrodynamics, quantum field theory, and general relativity, this article proposes that both the speed of light (c) and the light constant derived from Maxwell's equations are emergent properties, not fundamental absolutes. The propagation of light is shown to depend on the vacuum's mechanical properties—specifically, its elasticity, density, and viscosity. The constant $c = 1/\sqrt{\varepsilon_0 \mu_0}$ arises from the vacuum's electromagnetic response, where electric permittivity (ε_0) represents bulk elasticity and magnetic permeability (μ_0) corresponds to shear viscosity. By introducing a vortex-based vacuum model, the study further demonstrates that variations in vacuum density near massive objects lead to local reductions in the speed of light, thus providing a mechanistic explanation for gravitational time dilation. This unified model resolves apparent paradoxes between classical and quantum interpretations and offers a deeper understanding of the true nature and origin of light propagation, paving the way for a revised foundation in theoretical physics.

Keywords

Speed of Light Constant, Variable Speed of Light (VSL), Superfluid Vacuum, Omniom Vacuum, Vacuum Density, Vacuum Elasticity, Vacuum Viscosity, Shear Stress, Vacuum Compressibility, Gravitational Time Dilation, Vortex Model, Electromagnetic Permittivity, Magnetic Permeability, Photon Propagation

1. Introduction

The true nature of the photon and the origin of the speed of light c remain among the most enduring mysteries in physics. While quantum electrodynamics (QED) describes the photon as a massless quantum of the electromagnetic field with well-defined energy, momentum, and polarization, it provides little insight into the internal structure or origin of motion of the photon.

Historically, the photon emerged from efforts to reconcile the wave-like nature of light with experimental observations that revealed particle-like behavior, such as the photoelectric effect and Compton scattering. Einstein postulated that light is made up of quantized packets of energy, or photons, whose energy is directly proportional to frequency ($E = h\nu$) [1]. However, this particle-like description did not resolve questions regarding the physical structure of the photon, its rest mass, or the origin of its velocity in the vacuum.

Modern photon studies, particularly in single-photon (SP) experiments, have been pivotal in exploring quantum interference, entanglement, and the wave-particle duality at the heart of quantum optics and quantum information science [2]. Despite being classified as bosons and treated as massless gauge bosons in the Standard Model, photons show interaction features—such as polarization-dependent momentum transfer and fluctuations into fermion-antifermion pairs—that suggest a more complex substructure under high-energy conditions or in curved spacetime [3].

Recent theoretical frameworks and experimental observations challenge the long-held belief in the masslessness of the photon. Several experimental efforts—ranging from satellite magnetic field measurements to solar wind interactions and fast radio burst analyses—have placed upper limits on the photon rest mass, with results ranging from 10^{-50} to 10^{-54} kg [4]-[7]. Furthermore, the Proca equations, which generalize Maxwell's equations to allow for a nonzero photon mass, offer a plausible alternative to the standard picture, consistent with many observed phenomena.

In parallel, the physical interpretation of the speed of light and its associated constant c has evolved. While Einstein postulated in 1905 that light speed is invariant in all inertial frames—leading to the theory of special relativity—the deeper origin of this invariant speed remained unaddressed. According to Maxwell's equations, $c = 1/\sqrt{\varepsilon_0 \mu_0}$, yet this relation depends on vacuum permittivity and permeability, two quantities whose fundamental origin is also unknown. This raises the question: Is c truly fundamental, or is it emergent from the structure of the vacuum itself?

In recent work, the photon has been proposed to be a 3D spheroidal vortex structure embedded in a superfluid vacuum [8]-[10]. Within this model, the vacuum behaves as a fluid with density, elasticity, and compressibility, and the photon exhibits transverse and longitudinal spin. The speed of light in this context is no longer an unexplained postulate but rather a function of vacuum properties:

$$c = \sqrt{E/\rho}$$

where E is the vacuum elasticity and ρ is its density. The constant c emerges from the diminished momentum of the photon due to shear stress and bulk resistance in the vacuum. This reinterpretation aligns with hydrodynamic laws and allows derivation of photon parameters such as radius, frequency, and angular momentum from first principles.

Moreover, variable speed of light (VSL) theories suggest that c may not be truly constant, especially in curved or high-density regions of spacetime. Theories proposed by Einstein [11] [12], Dicke [13], and later Magueijo and Afshordi [14] point to gravitational potentials, vacuum density, and quantum fluctuations as possible modulators of the speed of light. These findings open the door to a more dynamic interpretation of the vacuum, where light speed may vary depending on cosmological or gravitational context.

This study aims to present a unified framework for understanding the structure of the photon and the physical origin of the light constant c. We apply classical hydrodynamic equations to a superfluid model of the vacuum, derive the photon's rotational properties and momentum, and propose that the speed of light is not fundamental but rather a consequence of the vacuum's superfluid and elastic characteristics. This reinterpretation offers new insights into quantum field theory, general relativity, and the foundational constants of nature.

2. The Vacuum as a Superfluid Medium

In quantum field theory and quantum electrodynamics (QED), the vacuum is not an empty void but a dynamic medium characterized by fluctuations and latent energy. This modern interpretation of the vacuum, often called the physical vacuum, includes a complex structure with measurable physical consequences [15]-[17].

The early conceptual groundwork was laid by Dirac, who proposed the idea of a sea of negative energy states, implying that vacuum is filled with virtual particles. This was further supported by experimental phenomena such as the Casimir effect and Lamb shift, confirming the presence of vacuum fluctuations [18].

More recent developments have modeled the vacuum as a superfluid quantum field, capable of supporting vortices and behaving like a non-dissipative, compressible fluid [9] [19] [20]. In such a superfluid model, the vacuum is characterized by:

- Ultra-high thermal conductivity,
- Zero viscosity or extremely low dissipation,
- High elasticity and compressibility,
- Absence of particulate structure,
- Ability to support quantized vortices.

Volovik [3] interpreted the vacuum as analogous to quantum liquids, such as helium-3, exhibiting superfluid properties at cosmic scales. In these analogies, elementary particles—such as electrons, quarks, and photons—can be viewed as topological defects or vortex excitations in the vacuum.

In this view, the vacuum possesses a measurable density and elasticity, which allow wave-like excitations such as the photon to propagate. This framework aligns with classical hydrodynamics, where the speed of wave propagation is given by:

This equation suggests that the speed of light is not a fundamental universal constant but an emergent property arising from the interaction between the photon and the structured vacuum [8].

Furthermore, Consoli and Costanzo argued for the existence of a quantum ether—a physical vacuum endowed with structure and dynamical behavior, capable of modulating the propagation of electromagnetic waves. The implication is that vacuum impedance, permittivity, and permeability are emergent from more fundamental vacuum dynamics [21].

In this context, the vacuum serves as the medium through which the photon travels. As the photon interacts with this medium, it experiences resistance through shear stress and bulk compressibility, leading to a diminished momentum that manifests as the constant. These resistive forces are analogous to viscosity and elasticity in classical fluids but occur at the quantum scale.

Therefore, the vacuum acts not as a passive backdrop but as an active and responsive superfluid medium that determines both the structure of the photon and the nature of light propagation. This approach enables the derivation of photonic parameters—such as radius, frequency, spin, and energy—from first principles, and unifies concepts from fluid dynamics, quantum field theory, and cosmology into a cohesive theoretical framework.

3. Vacuum Density: Foundations and Formulations

The concept of vacuum density has evolved significantly, particularly with the rise of quantum field theory and cosmology. The vacuum, once considered empty, is now viewed as a structured and energetic substrate permeating all space. Its density is not zero; instead, it plays a crucial role in governing cosmic expansion, the behavior of quantum particles, and the propagation of light [15]-[17].

3.1. Theoretical Basis

In classical general relativity, the cosmological constant (Λ) contributes to the vacuum energy density (ρ_{vac}), often associated with dark energy. This is expressed as:

$$\rho_{vac} = \left(\Lambda c^2\right) / \left(8\pi G\right) \quad [10]$$

However, quantum field theory predicts a much higher energy density arising from vacuum fluctuations. Although the predicted values diverge dramatically from observed cosmological densities—a discrepancy known as the cosmological constant problem—measurable estimations are possible from cosmological observations [17].

3.2. Cosmological Estimation via Hubble Expansion

From Hubble's Law, the expansion of the universe can be expressed as:

$$v = H_0 d \quad [22]$$

where:

- H_0 is the Hubble constant,
- d is the distance,
- v is the recession velocity.

Using this, the critical density of the universe is:

$$\rho_c = 3H_0^2 / (8\pi G)$$

Taking H_0 = 71.9 km/s/Mpc ≈ 2.33 × 10^{-18} s^{-1} and G = 6.67430 × 10^{-11} $m^3 \cdot kg^{-1} \cdot s^{-2}$, we compute:

$$\rho_c \approx 9.71 \times 10^{-27} \text{ kg/m}^3$$

This value aligns with the density required to explain the flat geometry of the universe and serves as an estimate of the vacuum's large-scale average density [22].

3.3. Derivation from Electromagnetic Constants

Alternatively, the vacuum density can be derived from the vacuum's electromagnetic properties. Using the speed of light equation:

$$c = \sqrt{E/\rho} \Rightarrow \rho = E/c^2 \quad [8]$$

where:

- E is the vacuum elasticity (bulk modulus),
- c = 3 × 10^8 m/s.

Assuming E = 8.87337441 × 10^{-10} $kg \cdot m/s^2 \cdot m^2$, we find:

$$\rho \approx 8.87 \times 10^{-10} / (9 \times 10^{16}) = 9.86 \times 10^{-27} \text{ kg/m}^3$$

This result corroborates the cosmological derivation and supports the hypothesis that the vacuum has intrinsic structure and substance.

3.4. The Gravitational Constant (G) as a Function of Vacuum Density and Drag Resistance

The gravitational constant G is one of the most fundamental constants in physics, governing the strength of gravitational interactions between masses. Traditionally, G has been treated as a fixed quantity with little connection to the properties of the vacuum. However, the Omniom vacuum hypothesis provides a new perspective, interpreting G as an expression of the vacuum's resistance to the displacement of density, akin to a drag force [15].

In this model, the drag force per unit volume of the vacuum is directly proportional to the gravitational constant G. The pressure gradient generated by this drag can be described as:

$$P = 0.5 \times C_D \times c^2 \times \rho \quad [7]$$

where:

- P = 6.67383255 × 10^{-11} $kg/m \cdot s^2$,

- $C_D = 0.156$ (drag coefficient),
- $c = 3 \times 10^8$ m/s.

Rearranging the drag pressure equation to solve for ρ:

$$\rho = 2P/\left(c^2 C_D\right)$$

Substituting the known values:

$$\rho = 2 \times 6.67383255 \times 10^{-11} \Big/ \left(\left(3 \times 10^8\right)^2 \times 0.156\right) \approx 9.51 \times 10^{-27}\ \text{kg/m}^3$$

This value matches cosmological estimates for the density of dark energy, suggesting that G inherently encapsulates the vacuum's resistance properties.

3.5. Unified Interpretation

Cosmological, electromagnetic, and gravitational approaches converge on the value $\rho \approx 10^{-27}$ kg/m³, suggesting that vacuum density is a physically meaningful and quantifiable quantity. This vacuum density, called the Omniom in recent theoretical frameworks [8] [10], underpins not only the expansion of space but also the propagation of particles and light.

Understanding vacuum density lays the foundation for interpreting the speed of light c as an emergent property of the vacuum's material characteristics, leading to deeper unification between quantum mechanics, general relativity, and cosmology.

4. Mechanical Interpretation of Light Propagation and the Role of Vacuum Constants

The speed of light, traditionally regarded as a fundamental constant, can be interpreted as an emergent property arising from the physical characteristics of the vacuum—namely, its density and elasticity. In contrast, the speed of light constant defined by Maxwell's equations emerges from the vacuum's electric permittivity (ε_0) and magnetic permeability (μ_0), which correspond to the vacuum's elastic and viscous properties, respectively.

4.1. Why Speed of Light Depends on Elasticity and Density

In classical mechanics, the speed of sound (v) in a medium is determined by:

$$v = \sqrt{\frac{K}{\rho}}$$

where:

K: bulk modulus (elasticity),

ρ: density of the medium.

This formula describes how faster wave propagation occurs in stiffer and lighter media. Drawing an analogy with the electromagnetic wave propagation in vacuum, we interpret the speed of light (c) as:

$$c = \sqrt{\frac{E}{\rho}}$$

where:

E: vacuum elasticity (bulk modulus),

ρ: vacuum density.

Thus, light propagates in the vacuum at a speed determined by its elastic resistance to deformation and its inertial density. This connection allows a mechanical analogy to explain photon motion as that of a pressure wave through a superfluid medium.

Maxwell's equations yield the wave speed in vacuum as:

$$c = 1\Big/\sqrt{\varepsilon_0 \mu_0}$$

This defines c not just as a wave speed, but as an invariant property linked to two material constants:

ε_0: electric permittivity, describing how the vacuum responds to electric field displacement,

μ_0: magnetic permeability, describing how the vacuum resists the formation of magnetic fields.

Hence, ε_0 can be interpreted as elasticity, while μ_0 relates to viscosity.

4.2. Electric Permittivity as an Expression of Vacuum Elasticity

In classical mechanics, bulk elasticity refers to the material's resistance to uniform compression and is quantified by the bulk modulus K. It is defined as the ratio of volumetric stress to volumetric strain and determines how much pressure is required to compress a material by a certain volume. The greater the bulk modulus, the stiffer the medium. In fluids and gases, this property governs the speed at which pressure waves, such as sound or electromagnetic waves, propagate through the medium.

Electric permittivity ε_0 measures the vacuum's capacity to permit electric field lines. It is a critical parameter in defining how electric charges interact and how electromagnetic fields propagate.

In analogy with bulk elasticity in mechanics [8]:

$$K = \rho c^2 \quad \text{or} \quad K = \frac{\rho}{\varepsilon_0 \mu_0}$$

Rewriting [18]:

$$\rho = \varepsilon_0 \mu_0 K$$

Using known values:

$$\varepsilon_0 = 8.854 \times 10^{-12}\ \text{F/m},$$

$$\mu_0 = 4\pi \times 10^{-7}\ \text{N/A}^2,$$

$$K = 8.55 \times 10^{-10}\ \text{Pa}$$

We obtain:

$$\rho \approx 9.51 \times 10^{-27}\ \text{kg/m}^3$$

This confirms that ε_0 can be treated as an elastic modulus on the electromagnetic scale.

4.3. Magnetic Permeability as an Expression of Vacuum Viscosity

Magnetic permeability μ_0 characterizes the vacuum's resistance to magnetic field formation. This resistance can be likened to shear stress, where magnetic interaction is viewed as a type of internal friction or viscosity.

Consider the interaction between a moving particle and vacuum. The momentum imparted through vacuum viscosity is:

$$P = \frac{\rho c}{\lambda}$$

where:

λ: Compton wavelength (e.g., 2.4263×10^{-12} m),

$\rho = 9.76 \times 10^{-27}$ kg/m^3,

$c = 3 \times 10^8$ m/s.

This matches the unit of μ_0, reinforcing the interpretation that μ_0 quantifies the vacuum's viscous response.

In electromagnetism:

$$\mu_0 = \frac{P}{tI^2}$$

where:

t: time,

I: current generating the magnetic field.

This dynamic resistance resembles viscosity as defined in hydrodynamics.

To validate this formula, consider the previously calculated momentum:

$$\begin{aligned} P &= \frac{\rho \times c}{\lambda} \\ &= \left(9.76 \times 10^{-27}\ \text{kg}/\text{m}^3 \times 3 \times 10^8\ \text{m}/\text{s}\right) \Big/ \left(2.4263 \times 10^{-12}\ \text{m}\right) \\ &\approx 1.206572 \times 10^{-6}\ \text{kg} \Big/ \left(\text{m}^2 \cdot \text{s}\right) \end{aligned}$$

Assuming:

$$t = 1\ \text{s}$$
$$I = 1\ \text{A}$$

Then:

$$\begin{aligned} \mu_0 &= \frac{P}{t \times I^2} \\ &= 1.206572 \times 10^{-6} \Big/ \left(1 \times 1^2\right) \\ &= 1.206572 \times 10^{-6}\ \text{N} \cdot \text{s}/\text{A}^2 \end{aligned}$$

This matches the known value of magnetic permeability in vacuum, confirming that the expression for μ_0 as a function of momentum, time, and current is consistent.

5. Variable Speed of Light and the Role of Vacuum Density

The variable speed of light (VSL) is a family of hypotheses suggesting that the speed of light in a vacuum may not be a true constant but can vary in time, space, or under different conditions such as frequency. The idea was initially proposed by Einstein in the context of general relativity, where he noted that clocks in a gravitational field run slower, leading to a shift in frequency:

$$\nu_1 = \nu_2 \left(1 + \frac{GM}{rc^2}\right)$$

here:

- frequencies measured at different gravitational potentials,
- gravitational constant,
- mass of the gravitating object,
- radial distance from the mass,
- speed of light.

Einstein's analysis laid the groundwork for VSL theories by connecting the variation of frequency to gravitational potential [11] [12]. Robert Dicke later developed a related VSL theory in 1957 [13], extending the idea to include changes in wavelength as well.

Subsequent theoretical developments included cosmological models where the speed of light was significantly higher in the early universe. Magueijo and Afshordi [14] proposed that near the Big Bang, light velocity was effectively infinite due to extreme temperatures and energy densities. Such behavior might be observable through imprints in the cosmic microwave background (CMB).

5.1. Electromagnetic and Gravitational Contexts for Light Speed Variation

In classical electromagnetism, the speed of light is considered constant only in an ideal vacuum. In media or under varying field densities, light slows down due to interactions with the medium. Similarly, if the vacuum itself is treated as a structured fluid with density and elasticity, the speed of light becomes:

$$c = \sqrt{\frac{E}{\rho}}$$

Thus, when vacuum density varies—especially near massive objects like stars or black holes—the speed of light must change accordingly.

General relativity reinforces this view: time dilation implies that at different altitudes or gravitational potentials, clocks tick at different rates. Since speed is defined as distance over time:

$$v = \frac{\text{distance}}{\text{time}}$$

a slower ticking clock implies longer time for the same spatial interval, thus a reduced effective velocity.

In highly curved spacetime regions (e.g., near a singularity), vacuum density increases, leading to time dilation and thus, via the above relation, a slower propagation speed for light. Conversely, in flatter regions of space, lower density permits faster light speed.

5.2. Hydrodynamic Analogy and Viscous Considerations

If we treat the vacuum as a superfluid medium, both its viscosity (η) and stiffness (inverse of elasticity, ε) become relevant. In this frame, the speed of light constant (c) from Maxwell's equations can be reformulated as:

$$c = \frac{1}{\sqrt{\eta\varepsilon}}$$

here,

- η is the vacuum viscosity (related to magnetic permeability μ_0),
- ε is the vacuum stiffness or inverse bulk modulus (related to electric permittivity ε_0).

Both and are affected by local vacuum conditions. Thus, in denser regions of space (e.g., near galaxies or black holes), these parameters change, resulting in a shift in the effective speed of light.

5.3. Radius-Dependent Density and the Vortex Model

Applying the classical equation of velocity $v = \frac{\text{distance}}{\text{time}}$ it follows that when more time is required to traverse the same distance—as occurs near massive objects—velocity effectively decreases. This is especially relevant in regions of strong gravitational fields, where space-time curvature is accompanied by increased vacuum density.

In a vortex-based vacuum model, we define the vacuum pressure force exerted at a radial distance (r) as:

$$F = \rho c^2 \pi r^2$$

Solving for the vacuum density ρ gives:

$$\rho(r) = \frac{F}{c^2 \pi r^2}$$

This shows that vacuum density increases as the radius r decreases, which occurs naturally near gravitational centers like stars or black holes.

As a result, the local speed of light becomes a function of radius:

$$c(r) = \sqrt{\frac{E}{\rho(r)}} = \sqrt{\frac{E\pi r^2}{F}}$$

The variation in speed of light induces gravitational time dilation, explaining why time slows down as one approach a massive body:

$$\Delta t' = \Delta t\sqrt{1 - \frac{2GM}{rc^2}}$$

In this framework, the gravitational field affects vacuum density, which in turn affects , providing a mechanistic explanation for the changes in both time and light speed as a function of radial position.

6. Discussion

The findings presented in this study challenge the conventional assumption that the speed of light is an immutable fundamental constant. Instead, we propose a paradigm in which light propagation is governed by the mechanical properties of a structured, superfluid-like vacuum medium—referred to as the Omniom. This vacuum exhibits quantifiable elasticity, viscosity, and density, enabling the derivation of the speed of light and its variation near massive bodies.

By interpreting vacuum permittivity as an expression of bulk elasticity and magnetic permeability as a measure of vacuum viscosity, we bridge electromagnetic theory with classical fluid mechanics. The hydrodynamic analogy provides new explanatory power, especially when considering shear stress and compressibility as causes of diminished momentum during light propagation.

The model explains gravitational time dilation and supports variable speed of light (VSL) theories through radius-dependent vacuum density calculations derived from vortex pressure forces. These dynamics offer a coherent framework that unifies general relativity, quantum field theory, and hydrodynamics under a common physical interpretation.

Furthermore, this model predicts that variations in local vacuum density will alter not only the speed of light but also other constants that depend on electromagnetic wave propagation, such as impedance and refractive index. This opens new experimental avenues for verifying the proposed theory via cosmological observations or precision measurements near gravitational wells.

7. Conclusions

This work introduces a novel and physically grounded framework that redefines the nature and origin of the speed of light. Contrary to its conventional status as a fundamental constant, we demonstrate that c emerges from the physical properties of the vacuum—specifically its elasticity, density, and resistance to shear. Within the proposed Omniom model, the vacuum behaves as a structured, compressible, superfluid medium, and the propagation of light is interpreted as a wave traversing this medium.

By treating the vacuum as a dynamic physical substrate, the speed of light is expressed as:

$$c = \sqrt{E/\rho}$$

where E is the vacuum's bulk modulus (elasticity), and ρ is its density. This relation reveals c to be a local property of the vacuum—variable under the influence of gravity, energy, or spatial curvature. This directly supports and extends Variable Speed of Light (VSL) theories, offering a mechanical and geometric foundation for frequency redshifts, gravitational lensing, and early-universe dynamics.

Furthermore, the model reinterprets Maxwell's constant $c = 1/\sqrt{\varepsilon_0 \mu_0}$ through a hydrodynamic lens, identifying:

- ε_0 as the vacuum's electric elasticity,
- μ_0 as its magnetic viscosity.

This approach demystifies electromagnetic constants by linking them to measurable mechanical properties of the vacuum, and opens the door to re-deriving other constants—including G, the gravitational constant—as emergent consequences of vacuum drag and compressibility.

Philosophically, this theory replaces abstraction with structure, restoring light to a medium—not as the outdated ether, but as a quantum-organized vacuum whose density and geometry govern the dynamics of energy, time, and matter. It bridges classical mechanics, general relativity, and quantum field theory under a single physical principle: resonance within a living vacuum.

By reimagining the speed of light not as a divine postulate but as the pulse of a structured cosmos, the Omniom model reawakens a unified understanding of spacetime, light, and gravitation—and lays a foundational stone for a new era in theoretical physics.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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