OPEN ACCESS
Modern Physics Letters A
(2025) 2550159 (18 pages)

DOI: 10.1142/S0217732325501597

Reinterpretation of the Michelson–Morley experiment and its consequences for cosmology

Václav Vavryčuk
Charles University, Faculty of Science, Albertov 6,
Prague 12800, Czech Republic
vavrycuk@natur.cuni.cz

Received 29 April 2025
Revised 5 July 2025
Accepted 31 July 2025
Published 24 September 2025

The Michelson–Morley (MM) interferometric experiment (Michelson and Morley [*Am. J. Sci.* **34**, 333 (1887), doi:10.2475/ajs.s3-34.203.333]) is one of the most pivotal experiments in modern physics, originally designed to detect a hypothesized anisotropy in the speed of light in vacuum due to aether drift. Contrary to this expectation, we show that the MM-type experiments are inherently incapable of detecting such drift. Their null result arises naturally from the Doppler effect acting on the interfering light beams, even in a frame moving relative to the aether. Consequently, the existence of aether cannot be excluded by these experiments. This interpretation remains consistent with Einstein's postulate of the constancy of the speed of light in vacuum, provided phase velocity, rather than group (signal) velocity, is considered. Our findings align with modern astrophysical and cosmological observations of the cosmic microwave background (CMB), which strongly suggest the existence of a preferred stationary reference frame. This reinterpretation of the MM experiment also resolves well-known paradoxes in Special Relativity.

Keywords: Aether drift; classical wave theory; cosmic microwave background; Doppler effect; Lorentz transformation; speed of light.

PACS Nos.: 95.30.Sf, 95.75.Kk, 98.70.Vc, 98.80.−k, 98.80.Jk

1. Introduction

The Michelson–Morley (MM) experiment[1] is among the most discussed and consequential experiments in modern physics. It played a crucial role in the development of Special Relativity (SR) by Einstein,[2] providing experimental support for the theory. The experiment aimed to detect Earth's motion relative to the luminiferous aether, a hypothetical medium postulated for the propagation of light under classical wave theory. Michelson and Morley[1] hypothesized that Earth's motion through the aether, which would define a preferred reference frame, should induce anisotropy in the speed of light, detectable via interferometric measurements of light beams in perpendicular directions. However, their experiment yielded a "null result", meaning no detectable shift in interference fringes occurred upon rotation of the interferometer arms.[3–5]

The null result was interpreted by FitzGerald[6] and Lorentz[7] as evidence of length contraction along the direction of motion, caused by interaction of matter with the aether. Later, this hypothesis was extended with the concept of time dilation,[8] leading to the formulation of the principle of relativity and the postulate of constancy of the speed of light in all inertial systems.[9,10] Finally, Einstein[2] abandoned the concept of the aether, arguing that an "absolute stationary space" was unnecessary for developing electrodynamics and optics. MM-type experiments have since been repeated with increasing precision, consistently yielding null results.[11–17] These experiments are now fundamental tests of SR.

Although the theoretical framework underlying the MM experiment appears straightforward, its null result remains a subject of debate. Several researchers have challenged the conventional interpretation that the MM experiments: (1) disprove the existence of the aether, and (2) confirm the constancy (invariance) of the speed of light in vacuum in all inertial frames.[18–25] For instance, Guerra and de Abreu[26,27] and de Abreu and Guerra[28] argue that the MM experiment measured not the one-way, but the two-way speed of light. Hence, the isotropy of two-way speed is more relevant, and the postulate of the constancy of the speed of light should be understood in this weaker form. Further critique comes from Consoli *et al.*[29] and Consoli and Pluchino,[30,31] who emphasize that MM-type experiments were conducted under different conditions: in vacuum, gases (air, helium), and solid dielectrics. However, these conditions could significantly influence results. They also note that the original MM experiment[1] did not yield a strictly null result but a small anisotropy, attributed at the time to measurement errors. Similar deviations were recorded by Morley and Miller,[11] Tomaschek[32] and Joos,[33] suggesting their possible physical origin, interpretable as weak velocity anisotropy due to interactions between aether and moving dielectric media.

Another major critique concerns the neglect of the Doppler effect in the null result interpretation, despite its well-established influence on frequency shifts and interference fringes.[20,34–36] Wesley[20,37] contends that a proper treatment of the classical Doppler effect can explain the null result even within an absolute spacetime framework. His approach is rooted in classical wave theory and offers several advantages:

- It applies not only to electromagnetic waves but also to other types of wave fields.
- It inherently incorporates the Doppler effect, whereas in SR, which is based on the Lorentz transformation, this effect is initially neglected. To reconcile SR with observations, the Doppler effect is introduced *ad hoc* into the relativistic calculations.[2]
- Neglecting the Doppler effect in the Lorentz transformation leads to inconsistencies and paradoxes in SR,[19,38–43] which do not arise in classical wave theory.

Wesley[20,37] also highlighted confusion in the standard interpretation of the MM experiment between phase velocity and group (signal, energy) velocity. Phase velocity appears in the wave equation and governs interference, while the group velocity (associated with the Poynting vector) governs energy transfer.[44] Even in a vacuum, these can differ, if the source or detector is moving. However, only phase velocity affects interference patterns. Despite this, SR presumes that the constant speed of light refers to the group velocity, thus introducing conceptual inconsistencies.

Lastly, a challenge to the conventional view arises from astrophysical observations of the Cosmic Microwave Background (CMB), discovered by Penzias and Wilson.[45] The CMB is highly isotropic, with a temperature of 2.7 K across the sky,[46] forming a natural Cosmological Coordinate System (CCS). This system is directly related to the mass distribution and its gravitational field in the Universe. Unlike the MM experiment, which failed to detect Earth's motion through the aether, the CMB dipole anisotropy, caused by the Doppler effect, provides a measurement of Earth's velocity in space.[30,47–52]

In this paper, we revisit the conventional interpretation of the MM experiment and identify errors in the analysis of its null result reported by Michelson and Morley.[1] We show that interferometric measurements can be accurately described within classical wave theory under the assumption of absolute spacetime. Central to this reinterpretation is the correct treatment of the Doppler effect via the Doppler transformation instead of the Lorentz transformation. This approach remains consistent with Einstein's postulate of the constancy of the speed of light, but assumes the invariance of phase velocity rather than group velocity. Our results align with CMB observations, reinforcing the idea of a preferred reference frame.

2. Theory

2.1. *Michelson–Morley formulas for the interference phase shift*

Here, we follow the original approach of Michelson and Morley.[1] Let d denote the distance between points A–B and A–C. The travel time of light along the x-axis (Fig. 1(a)) from A to C (forward propagation) is given by

$$T_{x1} = \frac{d}{c - v}, \tag{1}$$

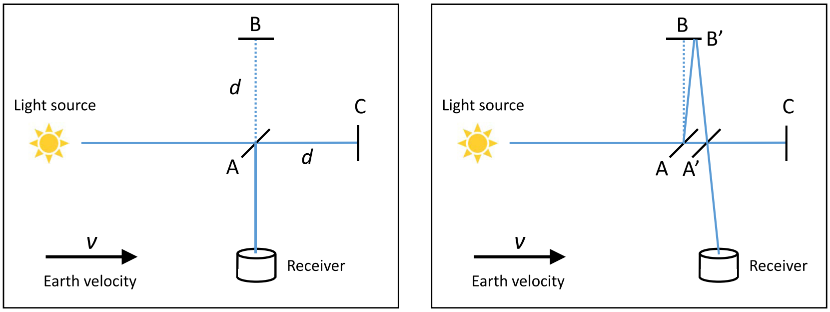
and the return time from C to A (backward propagation) is

$$T_{x2} = \frac{d}{c + v}, \tag{2}$$

where v is the velocity of the Earth relative to the aether, and c is the speed of light. Hence, the total travel time along the x-axis is

$$T_x = T_{x1} + T_{x2} = \frac{2dc}{c^2 - v^2} \approx \frac{2d}{c}(1 + \beta^2), \tag{3}$$

where $\beta = v/c$.



(a) (b)

Fig. 1. Scheme of the Michelson–Morley experiment. (a) Propagation of light along the x-axis, (b) propagation of light along the y-axis.

Similarly, the total travel time along the y-axis (Fig. 1(b)) between points A–B′–A′ is

$$T_y = \frac{2d}{c}\sqrt{1+\beta^2} \approx \frac{2d}{c}\left(1+\frac{1}{2}\beta^2\right). \tag{4}$$

The difference in travel time between the two paths is then

$$\Delta T = T_x - T_y \approx \frac{d}{c}\beta^2. \tag{5}$$

Finally, the phase shift between the two interfering light beams is

$$\Delta\varphi = \omega\Delta T \approx \omega\frac{d\beta^2}{c}, \tag{6}$$

where ω denotes the angular frequency of light. If the apparatus is rotated by 90°, the phase shift will reverse in sign, leading to an observed total phase shift of $2\Delta\varphi$.

2.2. *Corrected formulation of the interference phase shift*

However, the original Michelson–Morley derivation of the interference phase shift, as presented in the previous section, is flawed. The fundamental misconception lies in neglecting the Doppler effect, which arises from the difference between phase velocity and group (signal) velocity of light. The Doppler effect causes variations in the angular frequency of light along different propagation paths, contradicting the assumption made by Michelson and Morley[1] that the frequency remains constant. Consequently, Eq. (6) is incorrect and requires modification.

The phase shift between the light beams can be evaluated in different reference frames. First, let us consider a "static" frame, which is at rest with respect to the aether. This is the same frame used in Sec. 2.1, where the original Michelson–Morley derivation was performed. The angular frequency of light propagating in this frame is denoted as ω. Since point C is moving relative to the static frame at velocity v, the angular frequency of light travelling along the x-direction and detected at point C is Doppler-shifted as

$$\omega_{x1} = \frac{c - v}{c}\omega. \tag{7}$$

Conversely, the angular frequency of light reflected at point C, travelling in the x-direction back and detected at point A, is

$$\omega_{x2} = \frac{c + v}{c}\omega. \tag{8}$$

Similarly, for light propagating along the y-direction between points A–B′–A′, the angular frequency is shifted as

$$\omega_y = \frac{\omega}{\sqrt{1+\beta^2}}. \tag{9}$$

By substituting Eqs. (1)–(4) and (7)–(9) into the phase-shift equation

$$\Delta\varphi = \Delta\varphi_{x1} + \Delta\varphi_{x2} - \Delta\varphi_y, \tag{10}$$

we obtain

$$\begin{aligned}\Delta\varphi &= \omega_{x1}T_{x1} + \omega_{x2}T_{x2} - \omega_y T_y \\ &= \omega\frac{d}{c}\left(\frac{c-v}{c-v} + \frac{c+v}{c+v} - 2\frac{\sqrt{1+\beta^2}}{\sqrt{1+\beta^2}}\right) = 0.\end{aligned} \tag{11}$$

The same result is obtained when considering a frame fixed with the apparatus. Let ω denote the angular frequency of light emitted from the light source, which is at rest with the interferometer. Since points A, B and C are also at rest relative to the light source, the detected angular frequency remains unchanged at every point. Moreover, the phase velocity of light remains constant at c in all directions (see Appendix A). Therefore, we obtain

$$\Delta\varphi = \omega\left(\frac{d}{c} + \frac{d}{c} - 2\frac{d}{c}\right) = 0. \tag{12}$$

Thus, we have demonstrated that the variation in light travel time due to the velocity of the aether is precisely compensated by the frequency shift caused by the Doppler effect. Consequently, the experiment must yield in vacuum a null result, meaning that the interference fringes remain unchanged when the MM apparatus is rotated, and the interferometer arms exchange positions.

This contradicts the widely held belief that the Michelson–Morley experiment should be sensitive to aether velocity. Consequently, the null result of the MM experiment cannot be used as evidence for invalidating the existence of the aether or a preferred reference frame.

2.3. *Phase velocity and group (signal) velocity of light*

As discussed in the previous section, Michelson and Morley,[1] along with subsequent researchers, focused on calculating the difference in travel times between the two interfering beams (signals), while neglecting the wave nature of light, which is characterized by its phase. In doing so, they conflated phase velocity with the group (signal) velocity (see Fig. 2), as emphasized by Wesley.[20,35] For example, for a light source at rest in the stationary frame, the group velocity v_g is related to the phase velocity c and the velocity v_{obs} of an observer as follows:

- $v_g = c - v_{\text{obs}}$ (observer moving with the wave),
- $v_g = c + v_{\text{obs}}$ (observer moving against the wave).

Thus, for any nonzero v_{obs}, the phase and group velocities of light differ. As demonstrated in Appendix A, the Doppler effect implies that the phase velocity c remains constant in vacuum in any frame regardless of the observer's motion. Consequently, the group velocity v_g must vary for a moving observer. Therefore, assuming that the group speed of light is constant in all frames contradicts the Doppler effect observations.

A similar conceptual oversight occurs in the derivation of the coordinate transformation between two mutually moving inertial frames in Special Relativity (SR). The transformation between the coordinates

$$x^\alpha = (ct, x, y, z) \quad \text{and} \quad x'^\alpha = (ct', x', y', z'), \tag{13}$$

is typically derived without considering the wave nature of light, i.e. without accounting for its phase. As a result, the Doppler effect is omitted, and the transformation is based on the assumption that the group velocity (but not the phase

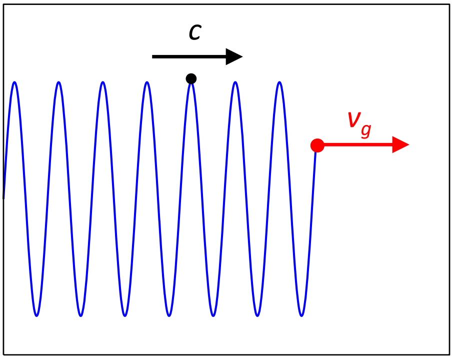


Fig. 2. Definitions of phase velocity c and group velocity v_g. The group velocity v_g is calculated as the relative velocity of the propagating signal (energy) with respect to the receiver. In contrast, the phase velocity c is given by the ratio of the wavelength λ to the period T of the wave measured at the receiver: $c = \lambda/T = \lambda\omega/2\pi$. While the signal velocity varies depending on the motion of the source and/or receiver, the phase velocity remains constant regardless of the reference frame used for its evaluation (see Appendix A).

velocity) is invariant in all inertial frames. This leads the Lorentz transformation[53]

$$\Lambda^{\mu}{}_{\nu} = \begin{vmatrix} \gamma & -\gamma\beta & 0 & 0 \\ -\gamma\beta & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}, \tag{14}$$

where $\gamma = 1/\sqrt{1-\beta^2}$ is the Lorentz factor, $\beta = v/c$, and v is the relative velocity along the x-axis. The determinant satisfies: $\det \Lambda^{\mu}{}_{\nu} = 1$.

By applying the transformation $\Lambda^{\mu}{}_{\nu}$ to the Minkowski metric tensor $\eta_{\mu\nu} = \mathrm{diag}(-1, +1, +1, +1)$, we obtain the transformed metric

$$g'_{\alpha\beta} = \Lambda^{\mu}{}_{\alpha}\, \Lambda^{\nu}{}_{\beta}\, \eta_{\mu\nu}, \tag{15}$$

which yields

$$g'_{\alpha\beta} = \eta_{\alpha\beta}. \tag{16}$$

This confirms that the transformed coordinate system x'^{α} also describes Minkowski space, with the invariant spacetime interval:

$$ds'^2 = -c^2 dt' dt' + dx'^{\,i} dx'^{\,i}, \tag{17}$$

predicting neither a shift in the angular frequency nor a change in the wavelength of light due to the Doppler effect. To resolve this inconsistency, SR artificially introduces the Doppler effect as an *ad hoc* correction to relativistic equation,[2] rather than deriving it from first principles.

2.4. *Dilation and contraction of time and length in classical wave theory*

Interestingly, when classical wave theory is applied and the Lorentz transformation is replaced with a Doppler-based transformation to relate the space and time coordinates between two mutually moving frames, the familiar effects of dilation/contraction of time and length known from SR still appear in the resulting formulas, as demonstrated below.

To correctly transform coordinates between two moving frames within the framework of classical wave theory, one must use the Doppler transformation, which explicitly accounts for Doppler shifts between frames in relative motion[54]:

$$D^{\mu}{}_{\nu} = \begin{vmatrix} \varepsilon\gamma & -\varepsilon\gamma\beta & 0 & 0 \\ -\varepsilon\gamma\beta & \varepsilon\gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}, \tag{18}$$

where the motion is assumed along the x-axis, $\gamma = 1/\sqrt{1-\beta^2}$ is the Lorentz factor, $\beta = v/c$, and ε is the Doppler factor. The Doppler metric tensor $g'_{\alpha\beta}$, resulting from the transformation $D^{\mu}{}_{\nu}$, is defined as

$$g'_{\alpha\beta} = D^{\mu}{}_{\alpha}\, D^{\nu}{}_{\beta}\, \eta_{\mu\nu}, \tag{19}$$

where $\eta_{\mu\nu}$ is the Minkowski metric tensor. Consequently, the spacetime interval becomes

$$ds'^2 = g'_{\alpha\beta} dx'^{\alpha} dx'^{\beta}, \tag{20}$$

which evaluates to

$$ds'^2 = -\varepsilon^2\, c^2 dt' dt' + \varepsilon^2\, dx' dx' + dy' dy' + dz' dz'. \tag{21}$$

This result shows that the Doppler factor ε naturally induces both time and length dilation or contraction. The effect depends on the relative velocity of the light source and the receiver, with respect to a stationary frame connected to the aether.[54] However, the physical interpretation of these effects in classical wave theory in Eq. (21) is fundamentally different from that in SR.

In classical wave theory, time and length dilation or contraction result from the frame-dependent nature of frequency and wavelength measurements. Consequently, dilation or contraction applies equally to both time and length. Specifically:

- If time is dilated, then length is also dilated.
- If length is contracted, then time is also contracted.

Importantly, these variations are apparent effects, relevant only to wave phenomena as observed from a given frame. Hence, "time" means the observed time period of light T, and "length" means the observed wavelength of light λ. Unlike in Special Relativity, they do not imply an actual change in physical time interval measured by atomic clocks or in real length of objects measured with rigid rods. In contrast to SR, where time dilation and length contraction are considered true physical effects, classical wave theory treats them as apparent frame-dependent observational effects of light's wave characteristics.

3. The Existence and Physical Nature of Aether

In classical wave theory, the preferred reference frame is defined as the frame in which the group (signal) velocity and the phase velocity of light are equal. This frame is both unique and physically meaningful, and it can be identified with the Cosmological Coordinate System (CCS), which is intrinsically linked to the mass distribution and gravitational field of the entire Universe.[55,56] In GR, it is described mathematically by the Friedmann–Lemaître–Robertson–Walker (FLRW) metric[57,58] or by the conformal cosmology (CC) metric.[59–64]

The existence of the CCS as a preferred frame is supported by modern cosmological observations of the Cosmic Microwave Background (CMB). Specifically, the CMB dipole anisotropy,[49,50,65,66] interpreted as a Doppler shift, reveals Earth's motion relative to this cosmologically defined rest frame. These measurements allow for precise determination of Earth's velocity with respect to the CCS. For the Solar System barycenter, this velocity is 370 km/s in the direction of the constellation Leo, with galactic coordinates: $l = 264°$, $b = 48°$. This constitutes direct empirical evidence for the existence of a preferred reference frame,[30] one that aligns with both classical wave theory and the philosophical underpinnings of Mach's principle.

The concept of a global stationary frame is closely linked to the notion of spacetime in GR, sometimes called absolute spacetime. Although Einstein initially rejected the aether and absolute motion,[2] he later reconsidered this in GR, recognizing the need for an aether-like entity in field theory. In his 1920 lecture Aether and the Theory of Relativity,[67] he introduced the idea of a "gravitational aether" — spacetime shaped by the cosmic gravitational field and described by the metric tensor $g^{\mu\nu}$. He suggested that aether and the gravitational field might be closely related, or even two expressions of the same physical reality.

Einstein's reinterpretation of aether under GR is also consistent with Mach's principle, which assets that local inertial frames — and thus the properties of motion and inertia — are determined by the global distribution of mass and energy in the Universe. In this framework, the structure of spacetime is shaped by cosmic matter, making a physically meaningful preferred frame both natural and necessary. From a GR standpoint, this preferred frame is associated with curved spacetime, which is no longer inertial. Therefore, the principle of relativity, as applied to inertial frames, is not valid in this context.

Furthermore, Einstein also abandoned the postulate of the constant speed of light in GR, when he stated[68]: "*The law of the constancy of the velocity of light in vacuo, which constitutes one of the fundamental assumptions in the special theory of relativity and to which we have already frequently referred, cannot claim any unlimited validity*" … "*its results hold only so long as we are able to disregards the influences of gravitational fields on the phenomena (e.g. of light)*". This view is consistent with modern interpretations of the cosmological and gravitational redshifts, where the phase speed of light in a vacuum is allowed to vary with cosmic time[62,69] and with spatial position due to spacetime curvature, e.g. near black holes.[70] In regions of strong gravitational fields, the speed of light is lower; in weak gravitational fields, it is higher. This behavior can be effectively modelled using a refractive index that characterizes the local gravitational field.

In fact, considering the vacuum with a gravitational field as a kind of a dielectric medium is a common approach in astrophysics. The refractive index n is defined as[53]

$$n = \frac{c}{c_g} = \frac{1}{\sqrt{g_{tt}}}, \tag{22}$$

where c and c_g are the phase speeds of light in vacuum without and with gravity, respectively, and g_{tt} is the time-time component of the spacetime metric tensor. This formalism has been adopted by many authors[71–78] to study photon geodesics using the tools of geometrical optics in dielectric media.

Since gravity affects both the geometry of light rays and the speed of light in the Universe, the gravitational field can be viewed as a principal component of the aether. Additional contributions may come from stationary electric and magnetic fields, which also affect light propagation and underlie well-known optical phenomena in dielectric media. The refractive index, shaped by all three types of fields, thus emerges as a potential unifying characteristic of the aether. This perspective points to a deeper connection between gravitational and electromagnetic fields than is typically acknowledged. Supporting this view is the observed equality of the speeds of gravitational waves and light, confirmed to high precision by recent astrophysical observations of neutron star mergers.[79,80]

4. Discussion

4.1. *Origin of misinterpretation*

In contrast to the standard interpretation of the Michelson–Morley experiment, we demonstrate that its null result is fully consistent with the existence of absolute spacetime or aether, as assumed in classical wave theory. The fundamental error made by Michelson and Morley[1] was their neglect of the Doppler effect in analyzing their experiment. Surprisingly, this interpretation was never critically reevaluated by leading physicists such as Lorentz, Poincaré, and others — likely due to the seemingly straightforward and intuitively convincing nature of Michelson's original derivation. Even Max Born, in his book Einstein's Theory of Relativity,[81] follows Michelson's original derivation based solely on light travel times, without attempting to evaluate the phases of light beams, a factor crucial to understanding the formation of interferometric fringes.

Notably, Einstein himself did not engage directly with the results of the MM experiment in his seminal paper on Special Relativity.[2] Instead, he constructed SR on the basis of simple and general postulates, placing little emphasis on experimental validation. As a result, Einstein regarded the concept of aether as unnecessary and replaced it with the postulate of the constancy (invariance) of the speed of light signal in a vacuum in all inertial frames. The null result of the MM experiment was subsequently viewed as a confirmation of SR, rather than as a finding requiring further scrutiny.

4.2. *Consequences for special relativity*

Since the null result of the MM experiment is widely regarded as key evidence supporting both the postulate of the constant speed of light in all inertial systems and the principle of relativity, revisiting its interpretation carries significant implications. In particular, the Lorentz transformation should be reconsidered, as it appears to inadequately describe coordinate transformations between moving frames.[43,54] A reassessment of time dilation and length contraction as real physical effects arising from relative motion between inertial frames also becomes necessary.[43] Furthermore, many well-known paradoxes in SR may stem from an incorrect treatment of the speed of light in spacetime transformations, specifically, by attributing it solely to the motion of photons as particles while neglecting its wave nature.

Clearly, the new interpretation of the MM experiment does not challenge all principles of SR:

- First, the principle of the constancy of the speed of light in a vacuum in all inertial frames remains valid even within classical wave theory. However, it applies specifically to the phase velocity, rather than the group (signal) velocity. This distinction is crucial, as the phase velocity determines the interference pattern in interferometric experiments and is therefore the key factor in interpreting the MM experiment. Furthermore, to remain consistent with GR, it should be emphasized that the constancy of the phase speed of light is not universally valid; rather, it holds locally, at a given time and within a limited region in the Universe.
- Second, time and space distortions are still present, albeit in a modified form, within classical wave theory. However, they arise from the Doppler effect rather than actual spacetime deformation. Crucially, these distortions are apparent effects caused by the transport delay of propagating light. Observing the Doppler effect does not imply a real distortion of physical time or space. The time rate remains the same in all frames, and physical length of objects measured by rigid rods does not change with velocity.
- Third, the famous mass-energy equivalence formula $E = mc^2$, originally developed by Poincaré,[82,83] while exploring electromagnetic momentum, can also hold within wave theory. Similarly, the principle that particles cannot exceed the speed of light is not in conflict with wave theory. However, the velocity of particles should be measured with respect to the CCS frame. If particle moves at a relativistic velocity in this frame, the energy required for further acceleration increases rapidly and diverges as the velocity approaches c. This effectively prevents a superluminal propagation of particles.

4.3. *Cosmological implications*

Reinterpreting the MM experiment within the framework of classical wave theory leads to replacing the Lorentz transformation with the Doppler transformation, which results in the Doppler metric. This metric has distinct properties, being conformal to Minkowski metric.[54] In cosmology, it aligns with the framework of Conformal Cosmology (CC), which differs significantly from the standard FLRW metric used to describe an expanding universe. Notably, the fundamental equations governing cosmic evolution take a different form in the CC metric compared to the FLRW metric. As a result, several longstanding issues in cosmology, such as the need for dark matter and dark energy in the Friedmann equations, are resolved within the CC approach. Moreover, the CC metric successfully predicts key observational phenomena, including flat galaxy rotation curves, galaxy expansion, and the morphology of spiral galaxies.[62,63,69]

4.4. *Further tests and future research*

Modern, newly designed MM-type experiments remain of great scientific value. As emphasized by Consoli *et al.*[29] and Consoli and Pluchino,[30,31] the original experiment by Michelson and Morley[1] did not yield an exactly null result, but rather a slight phase velocity anisotropy. This effect was also detected in other MM experiments.[11,32,33] While absent in vacuum,[15,84,85] this anisotropy has been observed in gaseous dielectric media. In such media, the interaction between the homogeneous cosmic gravitational field and moving local electric and magnetic fields must be considered. This interaction could, in principle, produce more complex effects including anisotropic behavior of the phase velocity of light. Therefore, careful and highly accurate interferometric measurements of velocity anisotropy in various dielectric media may provide new insights into the interaction between the gravitational and electromagnetic fields and their effects on light propagation.

Finally, the presented results should contribute to a re-evaluation and renewed appreciation of classical wave theory, and motivate further theoretical research in gravitation aimed at accurately describing the wave behavior of light in gravitational fields, the interactions between gravitational and electromagnetic fields, and the relationship between electromagnetic and gravitational waves. These efforts are essential for developing a unified theoretical framework. This objective is particularly compelling, as emphasized by Einstein in his 1920 lecture[67]: "*Of course it would be a great advance if we could succeed in comprehending the gravitational field and the electromagnetic field together as one unified conformation*".

Appendix A. A Constancy of the Phase Velocity of Light in Classical Wave Theory

Let us consider a static reference frame and assume that the speed of light is c in this frame. We analyze the phase velocity of light in the framework of classical wave theory under three different scenarios: (1) the light source is moving while the receiver is at rest, (2) the receiver is moving while the light source is at rest, and (3) both the light source and receiver are moving at the same velocity relative to the static frame.

(1) *Moving light source, stationary receiver.* If the light source moves at velocity v relative to the receiver, which is at rest, the angular frequency ω and wavelength λ of the emitted light are affected by the Doppler effect and can be expressed as

$$\omega = \frac{c}{c-v}\omega_0, \quad \lambda = \frac{c-v}{c}\lambda_0, \tag{A.1}$$

where ω_0 is the angular frequency of the light in the source's frame, and λ_0 is its wavelength measured in the source's frame. A positive velocity v indicates that the source is approaching the receiver, while a negative v indicates the source is receding. The phase velocity c of light, as measured in the source's frame, is given by

$$c = \frac{\lambda\omega}{2\pi} = \frac{\lambda_0\omega_0}{2\pi} = c_0. \tag{A.2}$$

Thus, the phase velocity remains constant despite the motion of the source.

(2) *Stationary light source, moving receiver.* If the light source is at rest while the receiver moves at velocity v, the Doppler effect alters the angular frequency ω and wavelength λ as follows:

$$\omega = \frac{c+v}{c}\omega_0, \quad \lambda = \frac{c}{c+v}\lambda_0, \tag{A.3}$$

where ω_0 and λ_0 are the emitted frequency and wavelength measured in the source's rest frame. A positive velocity v indicates that the receiver is approaching the source, while a negative v indicates the receiver is receding the source.

In this case, the phase velocity c of light, as measured in the receiver's frame, is

$$c = \frac{\lambda\omega}{2\pi} = \frac{\lambda_0\omega_0}{2\pi} = c_0. \tag{A.4}$$

(3) *Both light source and receiver moving together.* If both the light source and the receiver move at the same velocity v relative to the static frame, the Doppler effect is eliminated, meaning the angular frequency ω and wavelength λ remain the same in the frame of the light source and receiver. Consequently, the phase velocity of light is

$$c = c_0, \tag{A.5}$$

which is identical to the previous cases.

This analysis confirms that the phase velocity of light remains constant in all frames regardless of the relative motion of the light source or receiver with respect to the static frame connected to the aether. This result emphasizes that the principle of the constancy of the speed of light holds even within classical wave theory, provided that the phase velocity rather than the signal (group) velocity is considered.

Since the phase velocity is constant in all frames, it follows that the Michelson–Morley experiment must produce in vacuum a null result, even if the Earth is moving relative to the absolute spacetime. This contradicts the standard interpretation that MM-type experiments disprove the existence of a preferred reference frametext.

Acknowledgments

The author would like to thank the two anonymous referees for their reviews.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No new data were used in this paper.

ORCID

Václav Vavryčuk https://orcid.org/0000-0003-3962-2678

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