Definitive experimental test of Lorentzian Relativity

Simon WW Manley, Brisbane, QLD, Australia
ORCID: https://orcid.org/0000-0002-7396-691X
e-mail: SimonWWManley@gmail.com

Abstract In contrast with Special Relativity, the Lorentzian formulation allows absolute motion of the laboratory against a putative preferred frame of reference to be revealed by small but non-zero signals in Michelson-Morley experiments with light beams passing through a refractive medium. Testing this hypothesis, we developed a rotating Mach-Zehnder interferometer to compare the phase velocity of light in gas and vacuum. The new experiment reduces by three orders of magnitude the drift velocity against a preferred frame derived from historical Michelson-Morley data under the assumptions of Lorentzian Relativity, rendering this formulation untenable.

1 Introduction

The concept of a preferred frame of reference, such as the luminiferous aether of 19th century electromagnetic theory, was rendered superfluous in Special Relativity (SR) by the universal equivalence of inertial frames [Einstein, 1905]. The isotropy and constancy of the vacuum speed of light in this formulation guaranteed a null result in Michelson-Morley (M-M) experiments. SR has been orthodox for so long now that competing explanations for the experimental data are all but forgotten. Occasionally however, well-reasoned arguments [e.g. Consoli & Pluchino, 2023] are presented in favor of an earlier theoretical framework, Lorentzian Relativity (LR), which was the consensus of such luminaries as HA Lorentz, Henri Poincaré, Joseph Larmor and George F Fitzgerald around the year 1900.

In LR, a preferred frame of reference is concealed by a conspiracy of clock aberration and length contraction, rendering absolute motion undetectable and ensuring null results for M-M experiments [Lorentz, 1904]. The conventional view, formulated early in the 20th century and persisting to this day, holds that LR is experimentally indistinguishable from SR [Consoli & Pluchino, 2018b].

Arguments have been presented, however, that the experimental equivalence of SR and the LR is exact only in vacuum. As several authors have pointed out, LR predicts null results of M-M experiments because changes in light speed due to motion against the preferred frame are compensated by changes in the length of interferometer arms. Such compensation would no longer be exact if light were slowed in the optical pathways by a refractive medium [Cahill & Kitto, 2002; Cahill & Kitto, 2003; Consoli & Costanzo, 2003; Dmitriyev, 2011; Consoli, Matheson & Pluchino, 2013; Consoli, & Pluchino, 2021; Consoli & Pluchino, 2023]. Early M-M experiments were conducted in atmospheric air (refractive index, $n \approx 1.000\ 290$), or later helium ($n \approx 1.000\ 030$). The signal residuals reported were well short of classical predictions, justifying their traditional description as a "null result," but were in fact never precisely zero [Hicks, 1902; Miller, 1933].

It has been proposed that the small signal residuals in historical M-M experiments were actually consistent with relevant cosmic velocities if proper account is taken of the refractive medium in the optical pathways [Cahill & Kitto, 2002; Consoli & Pluchino, 2023]. The signal in a Michelson interferometer moving with velocity, v, against the preferred frame in LR was predicted to be proportional to the refractivity of the medium, $\varepsilon = n - 1 \approx 3 \times 10^{-4}$ for air, and to v^2/c^2, of the order of 10^{-6} for the velocity of the solar system with respect to the frame in which the dipole anisotropy of the Cosmic Microwave Background (CMB) radiation vanishes, $v = 369.82 \pm 0.11$ km/s [Planck Collaboration, 2020]. The combination of these small factors indicates that a Michelson interferometer of any practical dimensions could yield only miniscule signals, comparable to the level of noise and systematics characteristic of the old instruments. Distinguishing such signals from the precise null predicted by analyses using the full mathematical machinery of SR [Sfarti, 2009, 2011; Shanahan, 2014] remains contentious and arguments favoring the LR interpretation with a preferred frame of reference are at best plausible rather than convincing.

A novel M-M experiment was recently developed, employing a rotating Mach-Zehnder interferometer instead of the Michelson configuration to specifically measure the difference between the phase velocities of light in gas and vacuum [Manley, 2023; Manley, 2024]. Under the assumptions of LR, the new interferometer delivers a fringe-shift signal proportional to the first power of v/c. Gaining orders of magnitude in sensitivity compared with the Michelson design by virtue of the first-order response and the electronic registration of fringes to $10^{-4}\,\lambda$, this innovation permits the definitive testing of the LR interpretation of M-M experiments.

2 Historical Michelson-Morley experiments

The critical factor in any decisive experimental test is the magnitude of the signal in relation to the noise floor of the instrument. Interpretation of the historical data from M-M experiments requires the examination of signals at or near the limits of detection. Rather than simply perusing the well-known theory predicting the magnitude of fringe shifts in a rotating interferometer, it is therefore instructive to carry out precise numerical calculations (Table 1).

Let us first review the historical experiments of Dayton C Miller in the 1920s with a huge Michelson interferometer at Mt Wilson, near the astronomical observatory site [Miller, 1933]. Among the records of historical Michelson-Morley experiments, Miller’s dataset was the most extensive, totaling around 200,000 fringe shift readings recorded during 12,500 rotations of the largest interferometer constructed in that era. Despite the widespread acceptance of SR, Miller had remained convinced of a luminiferous aether acting as a preferred frame and dismissed the idea of Fitzgerald-Lorentz length contraction, attributing the shortfall of signal amplitudes in M-M experiments to the aether being “dragged” by matter. This belief motivated his years of repetitive work, resulting in a substantial data archive.

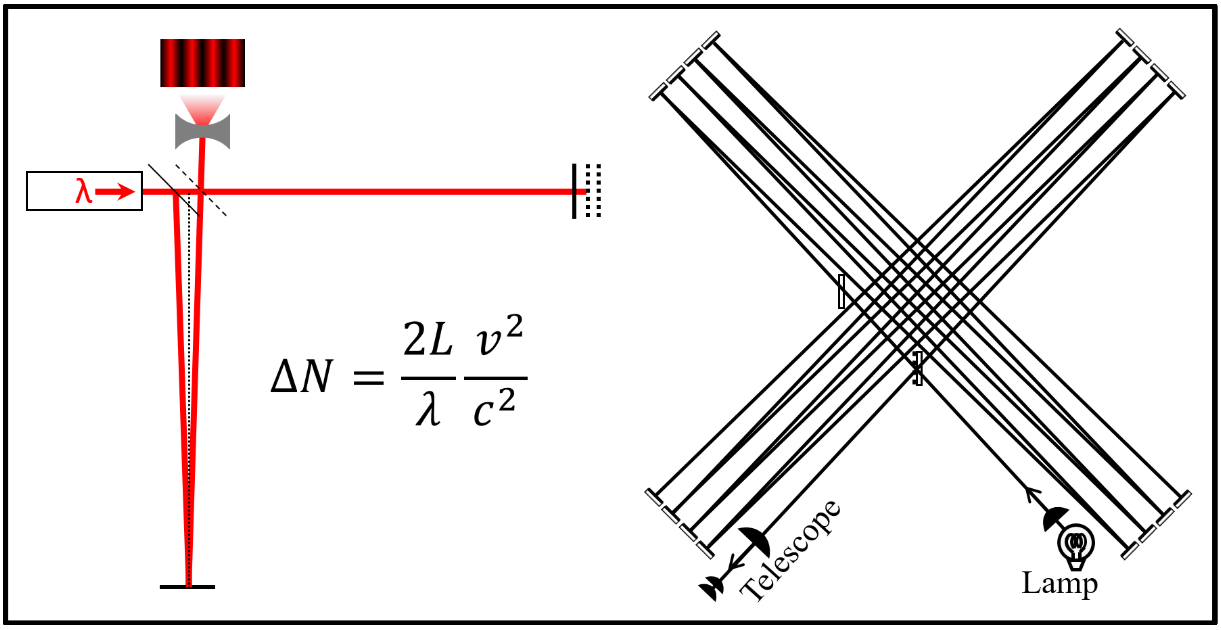

Fig. 1 On the left, the concept of the Michelson interferometer. The instrument is moving to the right relative to a preferred frame of reference. On the right, the optical paths in an implementation with 16 mirrors, used by Dayton C Miller in the 1920s at Mt Wilson.

Since the aim of the M-M experiment was to detect directional variations in the speed of light, it may seem logical to place the observer with the instrument at rest in the laboratory. A more convincing interpretation, however, comes from considering the observer to be at rest in the preferred frame while the interferometer moves (Fig. 1).

The phase velocity of light in the preferred frame is by definition isotropic. Our task is to calculate the relationship between the translational velocity and the shift in the interference fringe pattern caused by the difference in transit times for the wavefront in the arm parallel to the direction of motion and the arm perpendicular to the motion. The schematic of Miller's practical implementation of the Michelson interferometer [Miller, 1933] is illustrated in Fig. 1. The 19th century analysis assumed the linear addition of velocities inherent in classical physics and Galilean Relativity [Michelson & Morley, 1887]. Comparing the two-way transit times of light in orthogonal limbs of length, L, as the instrument moves against the preferred frame at velocity, v, predicted a peak-to-peak fringe shift on rotation, ΔN, given by:

$$\Delta N = \frac{2L}{\lambda}\frac{v^2}{c^2} \tag{1}$$

In Miller's instrument, the effective arm length was 32.030 m. The term $2L/\lambda$ was quoted as 1.12×10^8, implying an approximate wavelength for the yellow light from the oil lamp used in most of the work, $\lambda = 572$ nm. The objective of the historical M-M experiments was detection of the orbital motion of the Earth around the Sun at $v \approx 30$ km/s, $v/c \approx 10^{-4}$.

Replicating Miller's design calculations, we commence with the instrument static in the preferred frame (Table 1, values are femtoseconds). Neglecting the refractivity of air, we assume light propagates at its vacuum velocity of $c_{vac} \equiv 299\ 792\ 458$ m/s, so the transit times for a light wavefront are simply $T_0 = L/c_{vac} = 106\ 840\ 579.691\ 968$ fs, in each of the four directions. The wavelength, $\lambda = 572$ nm, corresponds to a period of 1.907 987 fs. Calculations were implemented at 15 significant figures, but rounded down in the table for readability.

Next, we consider the instrument moving at the Earth's orbital velocity, $v = 30$ km/s (Table 1, group 2). A light wavefront, leaving the beamsplitter to travel along the arm parallel to the direction of motion, overtakes the optical components at a speed, $c - v$. In the reverse direction, the wavefront advances at a relative speed, $c + v$. We note that the transit times are increased for the outward journey, decreased for the backward, but sum to a total which has increased compared with the static case. For ease of reading, numerical values in the table are shown as differences from the static value of the transit time, T_0.

The calculations for the arm perpendicular to the direction of motion are more intricate. The effect of motion against the preferred frame on light travel in the perpendicular arm was neglected in the earliest formulation of M-M experiments, which assumed that any such effect would be negligible [Cassini & Levinas, 2024]. Considering the effect of motion, we see that the beamsplitter has moved to the right during the travel of the wavefront out to the mirror and back (Fig. 1). The path lengths for light in the perpendicular arm are therefore no longer exactly L, but instead are the hypotenuse lengths of two (very narrow) right angled triangles. The increase in time in the perpendicular arm turns out to be half that in the parallel arms.

The difference between light propagation times in the two arms, under the assumptions of Galilean Relativity, with light propagating at its vacuum speed and motion against the preferred frame at a velocity of 30 km/s, was predicted to be about 1.07 fs, which is 0.56 of the period of the 572 nm light. Rotation effectively interchanges the arms of the instrument with each 90 degrees of turn, so the peak-to-peak shift in the interference fringe pattern becomes twice the difference from the static case. Miller expected a shift, $\Delta N \approx 1.12\ \lambda$, which would have been easily quantifiable as he read the fringe pattern by eye against a pointer, calling values in tenths of the fringe period for an assistant to record. Miller's copious records show, however, that the signal actually observed was an order of magnitude smaller than expectation, right at the limit of readability, $\Delta N \approx 0.1\ \lambda$.

Table 1: Transit times (fs) and signal amplitudes (ΔN as λ, p–p) for D.C. Miller's 1920s Michelson interferometer calculated under various assumptions

	Time Out	Time Back	Time Total	ΔT (fs)	ΔN (λ)
---{T_0 = 106 840 579.691 968 *fs*}---					
1: *Static, Vacuum*					
Parallel arm	T_0	T_0	$2T_0$		
Perpendicular	T_0	T_0	$2T_0$	0.000000	0.000000
2: *30 km/s, Vacuum, Galilean Relativity, no length contraction*					
Parallel arm	T_0 + 10692.524	T_0 – 10690.385	$2T_0$ + 2.139771		
Perpendicular	T_0 + 0.534943	T_0 + 0.53943	$2T_0$ + 1.069886	1.069886	1.121481
3: *30 km/s, Vacuum, Lorentzian Relativity, parallel arm length contracted*					
Parallel arm	T_0 + 10691.989	T_0 – 10690.919	$2T_0$ + 1.069886		
Perpendicular	T_0 + 0.534943	T_0 + 0.534943	$2T_0$ + 1.069886	0.000000	0.000000
---{T_a = 106 871 563.460 079 *fs*}---					
4: *Static, Atmospheric Air*					
Parallel arm	T_a	T_a	$2T_a$		
Perpendicular	T_a	T_a	$2T_a$	0.000000	0.000000
5: *30 km/s, Atmospheric Air, Lorentzian Relativity, parallel arm length contracted*					
Parallel arm	T_a + 10698.192	T_a – 10697.121	$2T_a$ + 1.071437		
Perpendicular	T_a + 0.535408	T_a + 0.535408	$2T_a$ + 1.070817	0.000621	0.000651
6: *371.880 km/s, Atmospheric Air, Lorentzian Relativity, parallel arm length contracted*					
Parallel arm	T_a+132690.61	T_a –132525.97	$2T_a$+164.63826		
Perpendicular	T_a + 82.271435	T_a + 82.271435	$2T_a$+164.54287	0.095393	0.100000
7: *369.82 km/s, Atmospheric Air, Special Relativity*					
Parallel arm	T_a +131878.54	T_a –131715.91	$2T_a$+162.63052		
Perpendicular	T_a + 81.315258	T_a + 81.315258	$2T_a$+162.63052	0.000000	0.000000

In contrast with Miller's expectations based on classical physics and Galilean Relativity, LR predicts a null result in vacuum (Table 1, group 3). The Lorentz-Fitzgerald contraction of the parallel arm reduces its length from L = 32.030 m to L/γ = 32.029 999 840 m, without affecting the perpendicular arm. The two-way travel times for the light wavefront in the parallel and perpendicular arms now match precisely. In vacuum, the prediction of LR is a null result.

With light propagating in a refractive medium, LR no longer predicts a null result (Table 1, group 5). In atmospheric air, with n = 1.000290, light speed reduces from the value $c_{vac} \equiv$ 299 792 458 m/s to c_{vac}/n = 299 705 543.392 416 m/s, a decrease of 0.029%. We have a new value for wavefront transit times in the static case, T_a = 106 871 563.460 079 fs (Table 1, group 4). With the instrument moving, the Lorentz-Fitzgerald length contraction, still governed by the vacuum speed of light, no longer compensates for the increase in transit time caused by motion against the preferred frame. The predicted signal at 30 km/s, ΔN = 0.000651 λ, though quite undetectable in the era of the historical M-M experiments, is definitively non-zero.

In contrast with SR, which of course predicts an exact null result for M-M experiments in any instrumental configuration, we see that LR predicts a non-zero signal when light in the optical pathways propagates through a refractive medium.

The question immediately follows: what cosmic velocity would have yielded a readable fringe shift with the equipment and techniques employed by Miller in his 1933 report?

Estimating fringe positions by eye, Miller reported a shift, $\Delta N \approx 0.1\ \lambda$. Under the assumptions of LR, this exact value of fringe shift would occur at a velocity, v = 371.880 km/s, with air of refractive index, n = 1.000290 in the optical pathways (Table 1, group 6). The agreement with the CMB dipole velocity of 369.82 km/s [Planck Collaboration, 2020] is striking [Cahill & Kitto, 2002; Consoli & Pluchino, 2023].

The skeptical reader will immediately suspect that the figures have been rigged to give such a precise agreement. The suspicious value is the refractive index of air, which in reality varies with barometric pressure and temperature. The values of 1.000280 or 1.000290 found in the literature discussing the LR interpretation of historical M-M experiments are plausible at sea level. At 1013 hPa pressure, a temperature of 20 C and relative humidity of 50% (typical for the author's laboratory at an elevation of only 40 m above mean sea level in Brisbane, Australia) the refractive index of air is n = 1.000273.

Miller, however, worked at the Mt Wilson site. The example record sheet shown in his 1933 report was for September 23, 1925, 2:57 to 3:19 AM at temperatures of 13.8–14.1 C. The barometric pressure was not recorded, but the site was at 1,740 m elevation, where air at 14 C has a standard pressure of 824 hPa. The NIST online calculator gives n = 1.000226. The cosmic velocity needed for a fringe shift value of ΔN = 0.1 increases to 421 km/s. This is still of the correct order, but the phenomenal match to the CMB dipole velocity reported in the literature for the refractive index, n = 1.000290, clearly represents a triumph of enthusiasm over realism.

A further complication in analysis of M-M experiments is the Fresnel drag effect, in which the velocity of light is altered by interaction with a moving medium. The equation below [Janssen, 2013] predicts the phase velocity of light, c_{nv}, in a medium of refractive index, n, moving at velocity, v. Under LR, where velocities add linearly, the equation is valid, though under SR, where velocity addition is nonlinear, it is only applicable for $v << c$ [Sfarti, 2011].

$$c_{nv} = \frac{c_{vac}}{n} + v\left(1 - \frac{1}{n^2}\right) \tag{2}$$

For atmospheric air, n = 1.000273, the expression in brackets evaluates to 0.000546. At the CMB dipole velocity of v = 369.82 km/s, the Fresnel drag effect alters the speed of light in the moving refractive medium by only 0.202 km/s. We could calculate the effect of this change on transit times in the interferometer, but there is a simpler workaround in the LR framework. Let us move our observer from the preferred frame of reference to a new frame moving in the direction of the drag at an appropriately small velocity, 0.000546 v. In this new frame, light propagation is isotropic, and our calculations remain qualitatively valid, with only a small quantitative error.

In contrast with the calculations above, SR predicts a null result (Table 1, group 7). An exact calculation cannot use the Fresnel drag equation, valid only as $v \to 0$. Instead, we must employ the transformation formulae for velocities as viewed from relatively moving frames. A wavefront moving at a velocity, w_x, with respect to a local frame which moves at velocity, v, in the x-direction is seen by an observer at rest to be moving at velocity, u_x, given by:

$$u_x = \frac{w_x + v}{1 + v w_x / c^2} \tag{3}$$

As light in vacuum is always observed at the same speed in SR, the equation of course yields $u = c$ for the case where $w = c$. For speeds approaching the limit set by the vacuum speed of light, such as the (slightly) reduced velocity of light in gas, the nonlinear velocity addition in SR has a drastic effect. Adding or subtracting the CMB dipole velocity, v = 369.82 km/s, to the phase velocity of light in air alters that velocity, as seen by our observer at rest, by only

+0.214 or –0.215 km/s. The increment in the two-way transit time for the light wavefront in the parallel arm in SR is less than that calculated under the assumptions of LR where addition of velocities is linear (Table 1, group 7 *vs*. group 6).

The calculation for the perpendicular arm is rather intricate, complicated by the vector calculation of the velocity in the diagonal path, but reduces to the simple expression, $2\gamma nL/c_{vac}$, matching the time for the parallel arm exactly and so yielding the null result. We also note that an observer moving with the instrument would measure the time for the two-way transit of the wavefront in each arm as $2nL/c_{vac}$. Our static observer in the preferred frame sees the moving observer's clock running slow, introducing the γ-factor.

A null result for M-M experiments in SR follows immediately without calculation, of course, from the assumption of universal equivalence of inertial frames. All observers must record readings from experimental apparatus which are independent of their state of motion.

We conclude that LR predicts a different result from SR, when M-M experiments are conducted with a refractive medium in the optical paths. The calculations in Table 1 reveal the origin of this difference. Departing from the assumptions of classical physics and Galilean Relativity, SR requires comparison of measurements in relatively-moving inertial frames to conform to the Lorentz transformations of length and time, to the nonlinear addition of velocities, and to the relativity of simultaneity. Predicting a null result for M-M experiments in vacuum requires only that classical expectations be augmented by the Lorentz-Fitzgerald length contraction. With a refractive medium in the optical paths, a null prediction also requires the nonlinear addition of velocities, respecting the light speed limit. Thus LR, which retains the classical assumption of linear velocity addition, predicts a small fringe shift with gas-filled Michelson interferometers moving against a preferred frame of reference, while SR predicts a null.

The interpretation of the signal residuals in historical M-M experiments remains a topic of ongoing debate in the literature. If a preferred frame of reference were definitively detected, revision of a substantial tract of physical dogma would be required. Conservative opinion demands the signals be dismissed as noise and systematics of thermal origin [Shankland *et al*., 1955]. It is apparent that further analysis of historical records is unlikely to convince either side of the debate. New data is required.

3 A new M-M experiment testing Lorentzian Relativity

The mainstream literature dismisses the signal residuals in early M-M experiments as instrumental systematics which diminished with technological progress over time, essentially vanishing with modern cryogenic experiments in vacuum or dense solids. The limits on Lorentz symmetry violation have been pushed down to $\Delta c/c \leq 10^{-18}$ in contemporary work [Muller et al., 2003; Tobar et al., 2006; Müller et al., 2007; Nagel et al., 2015]. If there is any interesting physics driving the anomalous signals in the historical data, it must be a function of the gas (air or helium) in the optical pathways of the old instruments. The Lorentzian interpretation of relativity, where motion against a preferred frame of reference might be revealed by reducing the phase velocity of light with a refractive medium, retains sufficient plausibility to justify investigation.

How might LR be tested in a modern laboratory? The notion of rebuilding one of the historical instruments, such as Miller's gigantic device, is preposterous. But today's optics and electronics allows the construction of a device of benchtop dimensions which matches or exceeds the sensitivity of the historical experiments to anomalous propagation of light in gas [Manley, 2023, 2024].

While developing a modern experiment, our conceptual breakthrough was separating tests for anisotropic refractivity in gases from tests of Local Lorentz Invariance. Since we know that light propagation in vacuum is isotropic to accuracy well beyond the anomalies we seek to study in gas, it follows that instead of testing orthogonal paths in air, as in the historical M-M experiments, we should test light propagation in air against propagation in vacuum. Thus we no longer require the orthogonal light paths of a traditional Michelson interferometer but are able to employ a Mach-Zehnder design with optical paths parallel and adjacent (Fig. 2).

By avoiding the awkward engineering of the Michelson design with its cross layout, we greatly improve mechanical stability. The theory of the instrument is simplified, the vacuum reference providing a perfect clock (constant length traversed at constant speed) against which to compare light propagation through the gas-filled path. Whereas the Michelson's two-way measure of light transit times incurs a response proportional to v^2/c^2 or $(\Delta c/c)^2$, the Mach-Zehnder instrument's one-way measurement confers a fringe shift signal which is first order in $\Delta c/c$. And Lorentz-Fitzgerald length contraction has negligible effect as it would influence the adjacent parallel pathways equally.

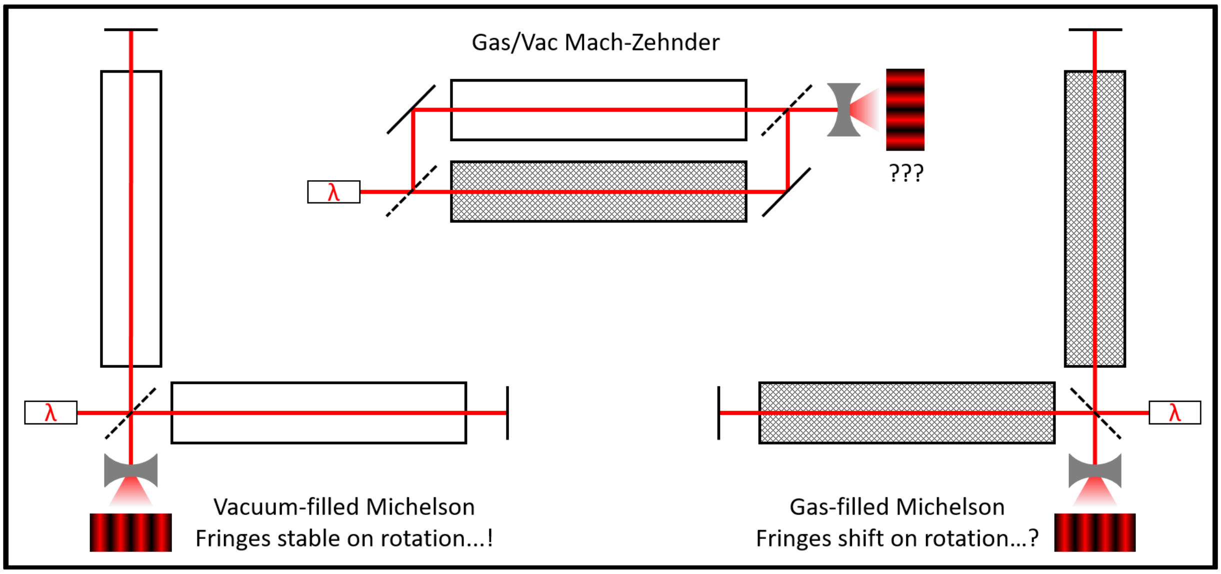

Fig. 2 Concept of a Mach-Zehnder interferometer testing for an anomaly of light propagation in gas. From modern experiments, we can be certain that a rotating Michelson interferometer would show a zero signal in vacuum. Historical gas-filled instruments, however, presented small anomalous fringe shifts. The Mach-Zehnder design directly compares gas with vacuum.

In a practical implementation of this concept [Manley, 2024], the straight path used for the gas (test) and vacuum (reference) beams was 530 mm, 1.00×10^6 λ for the 532 nm light from a diode-pumped solid-state laser (Thorlabs CPS532-C2). With electronic recording of interference fringe position, data from the instrument was taken in hourly blocks of 72 rotations with a period of 50 s per rotation (0.02 Hz). Fringe shift readings were recorded at 16 equally-spaced azimuth values during each rotation (an experimental design chosen to echo Miller's 1933 report).

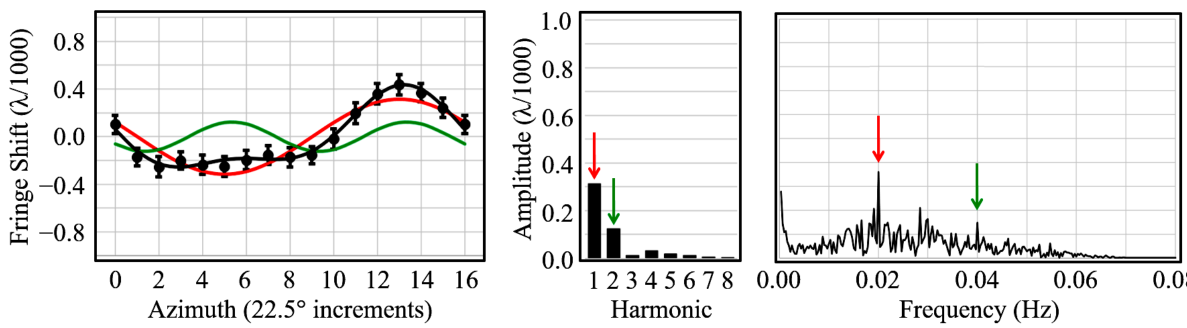

Fig. 3 Representative data from the new Mach-Zehnder interferometer. Left panel: signal treated as repeated measures of fringe shift readings at 16 azimuth directions during rotation (means ± S.E.M, n = 72). Cosine waves were fitted by least squares at the rotation frequency

(red, 0.02 Hz) and second harmonic (green, 0.04 Hz). Middle panel: amplitudes of harmonic components fitted by least squares from the fundamental up to the Nyquist limit (half the sampling frequency of 0.32 Hz). Right panel: Fourier spectrum of data treated as a continuous stream of readings at 0.32 Hz, after digital filtering to suppress baseline drift.

An illustrative example of processed data is shown in Fig. 3. Treating the data as 72 repetitions of fringe position measurements at each of the 16 azimuth values yielded a plot of the fringe shift during rotation as means ± standard errors of the means (SEM) with harmonic components fitted by least squares (Fig. 3, left panel; harmonic amplitudes in middle panel). Alternatively, the data could be treated as a continuous stream of 1152 readings taken at equal intervals, a format suitable for Fourier analysis. The spectrum revealed broadband noise in addition to a spike at the rotation frequency and often a (much smaller) spike at the second harmonic (Fig. 3, right panel). Variation in the amplitude of the fundamental remained in the range of 0.1 up to 1.0 in units of λ/1000 during daily and seasonal variations [Manley, 2024].

A significant innovation in the new design was the control configuration. Traditional M-M experiments, from the historical interferometers to modern devices with resonant cavities, have thus far provided a data stream consisting of putative signals summed with noise and the systematics caused by rotation. There has been no means of suppressing the signal to provide control data containing noise and systematics alone. With the new Mach-Zehnder design, physically meaningful signals were suppressed when the optical paths were balanced, the data consisting entirely of systematics and noise. Unbalancing the paths then permitted a putative genuine signal to add into the data stream, to be revealed as components of increased amplitude and/or altered phase compared with the controls [Manley, 2023, 2024].

In the control configuration (vacuum cell removed so test and reference beams traversed matching paths in air) the noise floor of the new instrument was 0.072 ± 0.004 in units of λ/1000 (n = 81). Removal or reinstallation of the vacuum cell (mass ≈ 0.3 kg) involved only minimal disturbance to the mechanics of the rotating chassis (mass ≈ 20 kg) carrying the optical components.

Unlike the analysis of the Michelson interferometer in traditional M-M experiments, which involves subtleties in the comparison of two-way measures of the phase velocity of light in orthogonal directions, the operation of the new Mach-Zehnder design is straightforward. A one-way comparison is made between a beam in vacuum and a beam with phase velocity reduced by the refractivity, $\varepsilon = n - 1$, of the gaseous medium. A change, Δc, in the vacuum speed of light would shift the interference fringe pattern by:

$$\Delta N = \frac{L}{\lambda} \varepsilon \frac{\Delta c}{c} \tag{4}$$

Having a response which is first order in $\Delta c/c$, the new instrument gained a large increase in sensitivity compared with the second order response of the Michelson. In the normal operating configuration of the Mach-Zehnder interferometer, where light propagation in air was compared with vacuum, the minimum discernable signal was about 0.1 units of λ/1000, corresponding to $\Delta c_{gas}/c_{vac} \approx 10^{-10}$, or $\Delta c_{gas} \approx 0.03$ m/s (note meters not kilometers per second). Compared with the historical M-M experiments reporting fringe shift residuals which could be interpreted as translational velocities, $v \approx 1 - 10$ km/s, the modern benchtop design gains 5 orders of magnitude in sensitivity to variations in the phase velocity of light in gas.

In Table 2, below, we calculate predicted signal amplitudes for the new instrument, under the assumptions of classical Galilean Relativity, LR and SR. As before, we place the observer at rest in a putative preferred frame, while the instrument moves at relevant velocities.

We begin by considering the Mach-Zehnder interferometer static in the preferred frame (Table 2, group 1). The optical path length, 0.530 m, was traversed in the vacuum reference pathway at $c_{vac} \equiv 299\,792\,458$ m/s, in a time $T_0 = 1\,767\,889.704\,550$ fs. The gas cell, containing air with refractive index, $n = 1.000\,273$, was traversed at $c_{vac}/n = 299\,710\,636.996\,100$ m/s, in a time of 1 767 372.338 440 fs. The time difference, 482.633 889 fs, was the zero offset for measurements of fringe shift and represented about 272 wavelengths, matching the shift in the fringe pattern as the reference cell was pumped down from atmospheric air to a hard vacuum. The shift in effective optical path lengths was about 0.145 mm, well within the coherence length of the laser source.

In groups 2 – 5 of Table 2, we compare the one-way transit times for the light wavefront through the vacuum and air paths, assuming linear addition of velocities in the Galilean and Lorentzian interpretations. For ease of reading, transit times were expressed as a difference from the time in vacuum at rest, T_0. We note that in the moving interferometer, times change with rotation as the laser beam propagates in the direction of the instrument's motion (denoted "Downstream"), and then in the opposite direction (denoted "Upstream").

Table 2: Transit times (fs) and signal amplitudes (A, λ/1000) for the new Mach-Zehnder interferometer calculated under various assumptions

Laser Beam	T vac (fs)	T air (fs)	T vac – T air	ΔT	A (λ/1000)
---{T_0 = 1 767 889.704 550 fs}---					
1: *Static in preferred frame*					
Downstream	T_0 + 0.000	T_0 + 482.634	482.633889		
Upstream	T_0 + 0.000	T_0 + 482.634	482.633889	0.000000	0.000000
2: *30 km/s, Galilean Relativity*					
Downstream	T_0 + 176.929	T_0 + 659.660	482.730511		
Upstream	T_0 – 176.894	T_0 + 305.644	482.537297	0.193214	54.440
3: *30 km/s, Lorentzian Relativity*					
Downstream	T_0 + 176.920	T_0 + 659.651	482.730508		
Upstream	T_0 – 176.903	T_0 + 305.635	482.537295	0.193214	54.440
4: *369.82 km/s {CMB dipole velocity}, Lorentzian Relativity*					
Downstream	T_0+2182.192	T_0+2,666.019	483.826633		
Upstream	T_0–2179.502	T_0–1,698.057	481.444819	2.381814	671.099
5: *0.165320 km/s {typical signal}, Lorentzian Relativity*					
Downstream	T_0 + 0.97490	T_0+483.60932	482.634422		
Upstream	T_0 – 0.97490	T_0+481.65846	482.633357	0.001065	0.300
6: *369.82 km/s {CMB dipole velocity}, Special Relativity*					
Downstream	T_0+2182.192	T_0+2664.826	482.634257		
Upstream	T_0–2179.502	T_0–1696.868	482.634257	0.000000	0.000000

Predicted signal amplitudes are large in relation to those actually observed, e.g. Fig. 3 and the previous report [Manley, 2024]. A typical signal would require a velocity some 3 orders of magnitude less than the CMB dipole (Table 2, group 5) and similarly less than the velocities inferred from signals in historical M-M experiments interpreted according to LR.

We note that Lorentz-Fitzgerald length contraction, predicted under the assumptions of LR to cancel the signal in traditional M-M experiments with Michelson interferometers, is without noticeable effect on the new instrument, where the optical paths are parallel rather than orthogonal (compare groups 2 & 3 of Table 2).

SR, of course, predicts zero signals in all M-M experiments. A trivial analysis places the observer stationary with respect to the instrument. Since SR demands light propagation be isotropic in all frames of reference, a zero fringe shift in M-M experiments is implicit.

The analysis for an observer watching a moving instrument under SR is rather more instructive, however. As in the analysis of the Michelson interferometer, we cannot rely on the Fresnel drag equation, but must apply the (nonlinear) transformation of velocities between relatively moving frames to obtain the correct values for the phase velocities of light in the refractive medium (Eq. 3). The difference between transit times in vacuum and air now match for the upstream and downstream directions, yielding a zero signal on rotation of the interferometer (Table 2, group 6).

In conclusion, we note that data from the new Mach-Zehnder instrument is in conflict with data from historical M-M experiments when interpreted under the assumptions of LR. Cosmic velocities deduced from signal amplitudes are 3 orders of magnitude less than those inferred from historical data.

4 Discussion

The original conception of the Michelson-Morley experiment was formulated in the framework of classical physics. Linear addition of velocities and constancy of lengths in relative motion, principles implicit in the absolute space and time of Newtonian physics and Galilean Relativity, were regarded as so elementary and self-evident they were not even worthy of identification as axiomatic assumptions underlying the analysis [Michelson & Morley, 1887].

The failure of rotating interferometers to demonstrate fringe shifts concordant with relevant cosmic velocities, such as the orbital speed of the Earth, was a crisis of paradigm-shifting import. The first hint of the revolution in theoretical physics which was to culminate in Einstein's 1905 formulation of SR came in a short letter by G.F. FitzGerald in 1889, proposing the contraction in length of moving objects [Fitzgerald, 1889].

By 1892, H.A. Lorentz, a leading theoretician of the era, had formulated the transforms for which he is now principally remembered. At the time of his lectures at Colombia University in 1906, Lorentz was convinced that the null result of M-M experiments provided irrefutable proof of the Lorentz-FitzGerald length contraction of moving objects [Lorentz, 1904; 1916]. Rather than being merely the consequence of a change in perspective due to relative motion, length contraction was a real physical effect according to Lorentz, mediated by changes in the behavior of atomic electrons.

Minkowski, meanwhile, was developing Einstein's ideas into the full mathematical machinery of electromagnetism in relativistic space-time [Minkowski, 1908]. Einstein initially characterized this elaboration as "überflüssige Gelehrsamkeit" – usually given a tactful translation as "superfluous erudition," but perhaps more accurately rendered as "overflowing learnedness."

In today's world, the debates on the foundations of relativity theory during the late 19th and early 20th centuries are all but forgotten, of more interest to historians than physicists. SR provides an entirely consistent system for the transformation of measurements between inertial frames in relative motion without acceleration or gravity. Refinements of M-M experiments testing Local Lorentz Invariance to higher and higher precision are no longer motivated by any doubts about the validity of SR, but instead by the prospect of quantum gravity phenomena expected in the Planck regime leaving subtle hints in a technologically accessible domain [Eichhorn, Platania & Schiffer, 2020].

An unresolved issue from the historical era concerns the small anomalous signals in M-M experiments with gas-filled interferometers. In 1955, Shankland and colleagues published a frequently-cited reanalysis of Miller's extensive data from the 1920s, attributing the signals to thermal fluctuations and gradients [Shankland *et al*. 1955]. The widespread acceptance of Shankland's work represented a collective sigh of relief from the physics community that a nagging issue in the foundations of SR could be laid to rest. A detailed reading of the paper, however, raises doubts of which no hint is to be found in the abstract. The only certain conclusion we can draw from the comparison of historical and modern M-M experiments is that gas in the optical pathways of interferometers was problematic.

In the 21st century, Reginald Cahill in Australia and Maurizio Consoli in Italy advanced novel proposals whereby the reduced phase velocity of light in the gas-filled optical pathways of historical M-M experiments might have conferred sensitivity to motion against a preferred frame of reference [Cahill & Kitto, 2002; Consoli & Costanzo, 2003]. The miniscule refractivity of atmospheric air, $\varepsilon = n - 1 \approx 3 \cdot 10^{-4}$, indicated that fringe shift signals would be orders of magnitude smaller than naïve predictions based on classical physics and thus would be consistent with the traditional picture of M-M experiments yielding null results. Under the new paradigm however, these small signal amplitudes became concordant with relevant cosmic velocities, such as the motion of the solar system against the CMB ($v \approx 370$ km/s) or against the rotating disk of our Milky Way galaxy ($v \approx 220$ km/s).

Considerable effort has been expended in reanalysis of historical records. The picture that has emerged is at best consistent with the new hypothesis, rather than compelling. The limitation in such analyses was the poor quality of the original data, which recorded signals close to the limits of detection.

The development of a novel M-M experiment, using a Mach-Zehnder interferometer to test light propagation in gas against a vacuum reference, now provides interpretative clarity [Manley, 2023, 2024]. Rather than the two-way measurement of light propagation in the Michelson interferometer, the new instrument compares one-way phase velocities, gaining orders of magnitude in sensitivity to anomalous propagation of light in gas. Translational speeds against a preferred frame of reference must be at least 3 orders of magnitude less than relevant cosmic velocities to predict the signal amplitudes typical of the modern instrument.

Thus we reject, with high confidence, the LR interpretation of M-M experiments where sensitivity to motion against a preferred frame of reference is conferred by a refractive medium reducing the phase velocity of light in the optical pathways.

It is instructive to dissect the characteristics of SR which, in contrast with the predictions of classical physics, conspire to yield a null result in M-M experiments. In an inertial observer's view of a relatively moving inertial frame, SR predicts contraction of lengths, slowing of clocks, disruption of simultaneity and the nonlinear addition of velocities. In vacuum, only the Lorentz-Fitzgerald length contraction is needed to predict a null result from M-M experiments. With a refractive medium in the optical pathways, nonlinear addition of velocities is also required for the null.

The rejection of the LR interpretation of M-M experiments leaves us with an unresolved question. What is the significance of the non-zero signals in historical M-M experiments and the—small but still non-zero—signals in our modern experiment?

Straightforward kinematic interpretations must be ruled out. The critical factor in the comparison of Michelson interferometers with the new Mach-Zehnder instrument is the two-way versus one-way measurement of light speed. With the two-way measure, gains and losses of speed caused by motion against a preferred frame would cancel to first order, leaving only a second order response, with a drastic reduction in sensitivity.

If we postulate that the Michelson and Mach-Zehnder instruments are actually—despite appearances—responding to the same physical phenomenon, then the mechanism affecting light propagation would have to avoid the cancellation of gains and losses of speed inherent in the two-way measure. This demands that the effect be non-directional (or omnidirectional), ruling out kinematics, but perhaps opening the door to another idea.

A minute temperature fluctuation of the gas in the optical pathways could alter light speed, changing density and therefore refractivity at constant pressure. Unlike a kinematic mechanism, this effect would avoid the first order cancellation inherent in two-way measures.

In a careful analysis of 6 historical M-M experiments, Consoli and Pluchino proposed a thermal effect of non-local origin, providing a plausible explanation for the signals and their reduced magnitude when helium ($n \approx 1.000\,030$) replaced atmospheric air ($n \approx 1.000\,290$) in the optical paths [Consoli & Pluchino, 2018a]. The temperature difference between the gas in orthogonal limbs of Michelson interferometers required to impose the requisite difference in phase velocities was 0.26 ± 0.06 ($n = 6$) mK. In this interpretation, the Michelson interferometer is vastly more sensitive to changes in the phase velocity of light than usually inferred. Miller's 1933 data, instead of implying $\Delta c/c \approx 3 \cdot 10^{-5}$, would signify $\Delta c/c \approx 2.5 \cdot 10^{-10}$ [Manley, 2024].

In our modern Mach-Zehnder instrument, a thermal cycle of 0.26 mK would yield an amplitude of 0.25 in units of $\lambda/1000$, matching our observed signals, as in Fig. 3 and the previous report [Manley, 2024]. The concordance of the new observations with historical data under the thermal proposal stands in sharp contrast with the severe conflict under kinematic analysis.

The mechanism of such a thermal cycle remains a matter of conjecture. The suggestion of a non-local coupling to the CMB dipole through the quantum mechanical vacuum [Consoli & Pluchino, 2018a] requires development of theory before it can yield a quantitative prediction of amplitudes.

Daily and seasonal cycles in the amplitude of signals from the new Mach-Zehnder interferometer were consistent with a celestial vector matching the predicted Dark Matter wind, rather than the CMB dipole [Manley, 2024]. This suggested a mechanism involving interaction with a field of moving particles having a low cross-section for interaction with baryonic matter, such as axions, which are currently regarded as plausible candidates for Dark Matter [Chadha-Day, Ellis & Marsh, 2022]. How such an interaction might confer the directional sensitivity implicit in the generation of a signal in rotating interferometers is not immediately obvious.

5 Conclusions

Data from a novel Michelson-Morley experiment with a rotating Mach-Zehnder interferometer comparing the phase velocity of light in air and vacuum is inconsistent with the Lorentzian interpretation of historical Michelson-Morley experiments, in which signal residuals were postulated to reveal motion against a preferred frame of reference. The conflict is 3 orders of magnitude in velocities inferred under kinematic assumptions. An alternative explanation is plausible: a fractional millikelvin cycle in the temperature of gas in the optical pathways during rotation of interferometers would account quantitatively for signals in the current work and the historical records. The mechanism driving such a thermal cycle is presently unknown: tempting speculations include a non-local coupling through the quantum mechanical vacuum to a cosmic vector or an interaction of gas with moving particles in the Dark Matter halo of our Milky Way galaxy.

6 References

Cahill, R. & Kitto, K. (2002). *Re-Analysis of Michelson-Morley Experiments Reveals Agreement with COBE Cosmic Background Radiation Preferred Frame so Impacting on Interpretation of General Relativity*. ***arXiv***:physics/0205070 [physics.gen-ph]. DOI: https://doi.org/10.48550/arXiv.physics/0205070.

Cahill, R. & Kitto, K. (2003). Michelson-Morley experiments revisited and the cosmic background radiation preferred frame. ***arXiv***:physics/0205065 [physics.gen-ph]. DOI: https://doi.org/10.48550/arXiv.physics/0205065

Cassini, A. & Levinas, L. (2024). *How the Michelson and Morley experiment was reinterpreted by special relativity*. ***arXiv***:2407.12960 [physics.hist-ph]. DOI: https://doi.org/10.48550/arXiv.2407.12960

Chadha-Day, F., Ellis, J. & Marsh, D.J.E. (2022). *Axion dark matter: What is it and Why Now?* ***Science Advances*** **8**, 8. DOI: https://doi.org/10.1126/sciadv.abj3618

Consoli, M. & Costanzo, E. (2003). *The motion of the Solar System and the Michelson-Morley experiment*. ***arXiv***:astro-ph/0311576. DOI: https://doi.org/10.48550/arXiv.astro-ph/0311576

Consoli, M., Matheson, C. & Pluchino, A. (2013). *The classical ether-drift experiments: a modern re-interpretation*. ***European Physical Journal Plus*** **128**, 71. DOI: https://doi.org/10.1140/epjp/i2013-13071-7

Consoli, M. & Pluchino, A. (2018a). *Cosmic microwave background and the issue of a fundamental preferred frame*. ***European Physical Journal Plus*** **133**, 295. DOI: https://doi.org/10.1140/epjp/i2018-12136-5

Consoli, M. & Pluchino, A. (2018b). *The classical Michelson-Morley experiments: A new solution to an old problem*. *Section 7*: *Light anisotropy in gases as a non-local thermal effect*. ***Atti della Accademia Peloritana dei Pericolanti - Classe di Scienze Fisiche, Matematiche e Naturali***, **96** (S1), A2. (*The text is in English*). DOI: https://doi.org/10.1478/AAPP.96S1A2

Consoli, M. & Pluchino, A. (2021). *The CMB, Preferred Reference System, and Dragging of Light in the Earth Frame*. ***Universe*** **7**, 311. DOI: https://doi.org/10.3390/universe7080311

Consoli, M. & Pluchino, A. (2023). Michelson–Morley experiments: at the crossroads of relativity, cosmology and quantum physics. ***International Journal of Modern Physics A***. **38**:35n36. DOI: https://doi.org/10.1142/S0217751X2330017X

Dmitriyev, V. (2011). *Absolute Motion Determined from Michelson-Type Experiments in Optical Media*. ***Zeitschrift für Naturforschung A***, **66**, 228-230. DOI: https://doi.org/10.1515/zna-2011-3-413

Eichhorn, A., Platania, A. & Schiffer, M. (2020). *Lorentz invariance violations in the interplay of quantum gravity with matter*. ***Physical Review D*** **102**, 026007. https://doi.org/10.1103/PhysRevD.102.026007

Einstein, A. (1905). *On the electrodynamics of moving bodies*. ***Annalen der Physik*** **17**, 891–921. In German, an English translation, based on Einstein (1923), *The Principle of Relativity* (Methuen, 1905) is online at: www.fourmilab.ch/etexts/einstein/specrel/www/

FitzGerald, G.F. (1889). *The ether and the earth's atmosphere*. ***Science*** **13**(328), 390–390. DOI: https://doi.org/10.1126/science.ns-13.328.390.a

Hicks, W.M. (1902) II. *On the Michelson-Morley experiment relating to the drift of the Aether*. ***The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*** Series 6, **3**, 9-42, DOI: https://doi.org/10.1080/14786440209462735

Janssen, M. (2013). *The drag coefficient from Fresnel to Laue*. *In*: Maas, A. & Schatz, H. (eds). *Physics as a calling, science for society: Studies in Honour of AJ Kox*. Leiden: Leiden University Press, 2013. p. 47-60.

Lorentz, H.A. (1904). *Electromagnetic phenomena in a system moving with any velocity smaller than that of light*. ***Proceedings of the Royal Academy Amsterdam*** **6**, 809-831. Also in: Collected Papers (1937). Springer, Dordrecht. DOI: https://doi.org/10.1007/978-94-015-3445-1_5

Lorentz, H.A. (1916). *The theory of electrons and its applications to the phenomena of light and radiant heat*; a course of lectures delivered in Columbia University, New York, in March and April 1906. New York: Columbia University Press. The book is available through many university libraries and as scanned page images of the 1923 reprint online through Hathitrust: https://babel.hathitrust.org/cgi/pt?id=uiug.30112062076283&seq=5

Manley, S.W.W. (2023). *A novel Michelson–Morley experiment testing for anisotropic light propagation in gas without violation of local Lorentz invariance*. ***European Physical Journal Plus*** **138**, 206. DOI: https://doi.org/10.1140/epjp/s13360-023-03812-w

Manley, S.W.W. (2024). *Experimental replication of the anomalous signal residuals in historical Michelson–Morley experiments with gas-filled interferometers indicates a celestial vector matching the predicted dark matter wind*. ***European Physical Journal Plus*** **139**, 730. DOI: https://doi.org/10.1140/epjp/s13360-024-05529-w

Michelson, A.A. & Morley, E.W. (1887). *On the relative motion of the Earth and the luminiferous ether*. ***American Journal of Science***, s3-34(203), 333–345. https://doi.org/10.2475/ajs.s3-34.203.333

Miller, D.C. (1933). *The Ether-drift experiment and the determination of the absolute motion of the earth*. ***Reviews of Modern Physics*** **5**, 203–242. DOI: https://doi.org/10.1103/RevModPhys.5.203

Minkowski, H. (1908). *Space and Time, a lecture given at the 80th Meeting of the Natural Scientists in Cologne on September 21, 1908*. In: *Minkowski's Papers on Relativity*. Minkowski Institute Press, Montreal, 2012, 134 pages. Available free online: http://minkowskiinstitute.org/mip/MinkowskiFreemiumMIP2012.pdf

Müller, H., Herrmann, S., Braxmaier, C., Schiller, S. & Peters, A. (2003). *Modern Michelson–Morley experiment using cryogenic optical resonators*. ***Physical Review Letters*** **91**, 020401. DOI: https://doi.org/10.1103/PhysRevLett.91.020401

Müller, H., Stanwix, P.L., Tobar, M.E., Ivanov, E., Wolf, P., Herrmann, S., Senger, A., Kovalchuk, E. & Peters, A. (2007). *Tests of Relativity by Complementary Rotating Michelson-Morley Experiments*. ***Physical Review Lett***ers **99**, 050401. DOI: https://doi.org/10.1103/PhysRevLett.99.050401

Nagel, M., Parker, A., Kovalchuk, A.E. *et al*. (2015). *Direct terrestrial test of Lorentz symmetry in electrodynamics to* 10^{-18}. ***Nature Communications*** **6**, 8174. DOI: https://doi.org/10.1038/ncomms9174

Planck Collaboration. (2020). *Planck 2018 results*. ***Astronomy & Astrophys***ics **641**, A1, (56 pp). DOI: https://doi.org/10.1051/0004-6361/201833880

Sfarti, A. (2009). *Simplified single postulate theory of relativity*. ***Physics Essays*** **22**, 223-224. DOI: https://doi.org/10.4006/1.3138103

Sfarti, A. (2011). *Comment on the Paper "Absolute Motion Determined from Michelson-Type Experiments in Optical Media" by V. P. Dmitriyev*. ***Zeitschrift für Naturforschung A***, **66**,791-794. DOI: https://doi.org/10.5560/zna.2011-0059

Shanahan, D. (2014). A Criticism of "Gas Mode" Reinterpretations of the Michelson-Morley and Similar Experiments. ***arXiv***:1404.6095 [physics.class-ph]. DOI: https://doi.org/10.48550/arXiv.1404.6095

Shankland, R.S., McCuskey, S.W., Leone, F.C. & Kuerti, G. (1955). *New Analysis of the Interferometer Observations of Dayton C. Miller*. ***Reviews of Modern Physics*** **27**, 167-178. DOI: https://doi.org/10.1103/RevModPhys.27.167

Tobar, M.E., Stanwix, P.L., Susli, M., Wolf, P., Locke, C.R. & Ivanov, E.N. (2006). *Rotating Resonator-Oscillator experiments to test Lorentz Invariance in Electrodynamics, in Special relativity*. ed. J. Ehlers, C. Lämmerzahl (Springer, Berlin Heidelberg, 2006), pp.416–450. DOI: https://doi.org/10.1007/3-540-34523-X_15