The Michelson-Morley experiment and the cosmic velocity of the Earth

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Abstract

The Michelson-Morley experiment was designed to detect the relative motion of the Earth with respect to a preferred reference frame, the ether, by measuring the fringe shifts in an optical interferometer. These shifts, that should have been proportional to the square of the Earth’s velocity, were found to be much smaller than expected. As a consequence, that experiment was taken as an evidence that there is no ether and, as such, played a crucial role for deciding between Lorentzian Relativity and Einstein’s Special Relativity. However, according to some authors, the observed Earth’s velocity was not negligibly small. To provide an independent check, we have re-analyzed the fringe shifts observed in each of the six different sessions of the Michelson-Morley experiment. They are consistent with a non-zero observable Earth’s velocity

\[ v_{\text{obs}} = 8.4 \pm 0.5 \text{ km/s}. \]

Assuming the existence of a preferred reference frame and using Lorentz transformations, this \( v_{\text{obs}} \) corresponds to a real velocity, in the plane of the interferometer,

\[ v_{\text{earth}} = 201 \pm 12 \text{ km/s}. \]

This value, which is remarkably consistent with 1932 Miller’s cosmic solution, suggests that the magnitude of the fringe shifts is determined by the typical velocity of the solar system within our galaxy. This conclusion is consistent with the results of all classical experiments (Morley-Miller, Illingworth, Joos, Michelson-Pease-Pearson,...) and with the existing data from present-day experiments.
1. The Michelson-Morley experiment \[1\] is generally believed to represent the proof that the Earth’s absolute motion cannot be detected in a laboratory experiment. However, the fringe shifts observed in the original experiment (and in the subsequent one of Morley and Miller \[2\]) although smaller than the expected magnitude corresponding to the orbital motion of the Earth, were not negligibly small. While this had already been pointed out by Hicks \[3\], Miller’s refined analysis of the half-period, second-harmonic effect observed in the experimental fringe shifts showed that they were consistent with an effective, observable velocity lying in the range 7-10 km/s (see Fig.4 of Ref.\[4\]). For instance, the Michelson-Morley experiment gave a value $v_{\text{obs}} \sim 8.8 \text{ km/s}$ for the noon observations and a value $v_{\text{obs}} \sim 8.0 \text{ km/s}$ for the evening observations.

The aim of this paper is twofold. On one hand, for the convenience of the reader, we shall explicitly illustrate some steps that are not immediately evident in the Michelson-Morley original paper and recalculate the values of $v_{\text{obs}}$ for their experiment.

On the other hand, by using Lorentz transformations, the small observed velocity will be shown to correspond to a real Earth’s velocity, in the plane of the interferometer, $v_{\text{earth}} \sim 200 \text{ km/s}$. This value, which is remarkably consistent with 1932 Miller’s cosmic solution \[4\], suggests that the fringe shifts are determined by the typical velocity of the solar system within our galaxy (and not, for instance, by its velocity $v_{\text{earth}} \sim 336 \text{ km/s}$ with respect to the centroid of the Local Group). In this sense, this paper provides a consistent and self-contained treatment of the Michelson-Morley type of experiments.

2. We have analyzed the original data obtained by Michelson and Morley in each of the six different sessions of their experiment. No form of inter-session averaging has been performed. As discovered by Miller, in fact, inter-session averaging of the raw data may produce misleading results. For instance, in the Morley-Miller data \[2\], the morning and evening observations each were indicating an effective velocity of about 7.5 km/s (see Fig.11 of Ref.\[4\]). This indication was completely lost with the wrong averaging procedure adopted in Ref.\[2\]. The same point of view has been advocated by Munera in his recent re-analysis of the classical experiments \[5\].

To obtain the fringe shifts of each session we have followed the well defined procedure adopted in the classical experiments as described in Miller’s paper \[4\]. Namely, starting from the seventeen entries, say $E(i)$, reported in the Michelson-Morley Table \[1\], one first has to correct for the difference $E(1) - E(17)$ between the first entry and the seventeenth entry obtained after a complete rotation of the apparatus. In this way, assuming the linearity of the correction effect, one adds $15/16$ of the correction to the 16th entry, $14/16$ to the 15th
entry and so on, thus obtaining a set of 16 corrected entries
\[ E_{\text{corr}}(i) = \frac{i - 1}{16} (E(1) - E(17)) + E(i) \]  
(1)

Finally, the fringe shift is defined from the differences between each of the corrected entries \( E_{\text{corr}}(i) \) and their average value \( \langle E_{\text{corr}} \rangle \) as
\[ \Delta \lambda(i) = E_{\text{corr}}(i) - \langle E_{\text{corr}} \rangle \]  
(2)

We have fitted the amplitude \( \bar{A}_2 \) of the second-harmonic component in a Fourier expansion (\( \theta = \frac{i - 1}{16} 2\pi \))
\[ \frac{\Delta \lambda(\theta)}{\lambda} = \sum_n \bar{A}_n \cos(n\theta + \phi_n) \]  
(3)

Following Miller’s indications, we have included terms up to \( n = 5 \), although the results for \( \bar{A}_2 \) are practically unchanged if one excludes from the fit the terms with \( n = 4 \) and \( n = 5 \). Our values of \( \bar{A}_2 \) for each session are reported in Table 1.

The Fourier analysis allows to determine the azimuth of the ether-drift effect, from the phase \( \phi_2 \) of the second-harmonic component, and an observable velocity from the value of its amplitude. To this end, we have used the basic relation of the experiment
\[ 2\bar{A}_2 = \frac{2D}{\lambda} \frac{v_{\text{obs}}^2}{c^2} \]  
(4)

where \( D \) is the length of each arm of the interferometer.

Notice that, as emphasized by Shankland et al. (see page 178 of Ref. [6]), it is the quantity \( 2\bar{A}_2 \), and not \( \bar{A}_2 \) itself, that should be compared with the maximal displacement obtained for rotations of the apparatus through 90° in its optical plane (see also Eqs. (23) and (24) below). Notice also that the quantity \( 2\bar{A}_2 \) is denoted by \( d \) in Miller’s paper (see page 227 of Ref. [4]).

Therefore, for the Michelson-Morley apparatus where \( \frac{D}{\lambda} \sim 2 \times 10^7 \) \( \text{[1]} \), it becomes convenient to normalize the experimental values of \( \bar{A}_2 \) to the classical prediction for an Earth’s velocity of 30 km/s
\[ \frac{2D}{\lambda} \frac{(30 \text{km/s})^2}{c^2} \sim 0.4 \]  
(5)

and we obtain
\[ v_{\text{obs}} \sim 30 \sqrt{\frac{\bar{A}_2}{0.2}} \text{ km/s} \]  
(6)

Now, by inspection of Table 1, we find that the average value of \( \bar{A}_2 \) from the noon sessions, \( \bar{A}_2 = 0.017 \pm 0.003 \), indicates a velocity \( v_{\text{obs}} = 8.7 \pm 0.8 \text{ km/s} \) and the average value from the evening sessions, \( \bar{A}_2 = 0.014 \pm 0.003 \), indicates a velocity \( v_{\text{obs}} = 8.0 \pm 0.8 \text{ km/s} \). Since the two
determinations are well consistent with each other, we conclude that the Michelson-Morley experiment provides an observable velocity

\[ v_{\text{obs}} = 8.4 \pm 0.5 \text{ km/s} \]  

(7)

This is also in agreement with the results obtained by Miller himself at Mt. Wilson. Differently from the original Michelson-Morley experiment Miller’s data were taken over the entire day and in four epochs of the year. However, after the critical re-analysis of Shankland et al. [6], it turns out that the average daily determinations of \( \bar{A}_2 \) for the four epochs are statistically consistent (see page 170 of Ref.[6]). In this case, if one takes the average of the four daily determinations, \( \bar{A}_2 = 0.044 \pm 0.005 \), one obtains a value which is just \( \sim 1/13 \) of the classical expectation for an Earth’s velocity of 30 km/s (see page 170 of Ref.[6]) and an effective \( v_{\text{obs}} \) which is exactly the same as in Eq.(7).

The problem with Miller’s analysis was to reconcile such low observable values of the Earth’s velocity with those obtained from the daily variations of the magnitude and azimuth of the ether-drift effect with the sidereal time. In this way, in fact, on the base of the theory exposed by Nassau and Morse [7], one can determine the apex of the motion of the solar system. By requiring consistency among the four different determinations obtained in the four epochs of the year (see Fig.23 of Ref.[4]), Miller could restrict kinematically the cosmic Earth’s velocity in the range 200-215 km/s (see page 233 of Ref.[4]) with the conclusion that ”...a velocity \( v_{\text{earth}} \sim 208 \text{ km/s} \) for the cosmic component, gives the closest grouping of the four independently determined locations of the cosmic apex”.

At the same time, due to the particular magnitude and direction of the cosmic component, Miller’s predictions for its projection in the plane of the interferometer had very similar values (see Table V of Ref.[4]), say

\[ v_{\text{earth}} \sim 203 \pm 8 \text{ km/s} \]  

(8)

Therefore, after Miller’s observations, the situation with the ether-drift experiments could be summarized as follows (see page 236 of Ref.[4]). On one hand, ”the observed displacement of the interference fringes, for some unexplained reason, corresponds to only a fraction of the velocity of the Earth in space”. On the other hand, the theoretical solution of the Earth’s cosmic motion involves only the relative values of the ether-drift effect and ”..does not require a knowledge of the cause of the reduction in the apparent velocity nor of the amount of this reduction”. A check of this is that, after plugging the final parameters of the cosmic component in the Nassau-Morse expressions, ”..the calculated curves fit the observations remarkably well, considering the nature of the experiment” (see Figs. 26 and 27 of Ref.[4]).
In spite of this beautiful agreement, the unexplained large discrepancy between the typical values of \(v_{\text{obs}}\), as given in Eq. (7), and the typical calculated values of \(v_{\text{earth}}\), as given in Eq. (8), has been representing a very serious objection to the consistency of Miller’s analysis.

It has been recently pointed out, however, by Cahill and Kitto \[8\] that an effective reduction of the Earth’s velocity from values \(v_{\text{earth}} = O(10^2) \text{ km/s}\) down to values \(v_{\text{obs}} = O(1) \text{ km/s}\) can be understood by taking into account the effects of the Lorentz contraction and of the refractive index \(N_{\text{medium}}\) of the dielectric medium used in the interferometer.

In this way, the observations become consistent \[8\] with values of the Earth’s velocity that are comparable to \(v_{\text{earth}} \sim 365 \text{ km/s}\) as extracted by fitting the COBE data for the cosmic background radiation \[9\]. The point is that the fringe shifts are proportional to \(\frac{v_{\text{earth}}^2}{c^2}(1 - \frac{1}{N_{\text{medium}}^2})\) rather than to \(\frac{v_{\text{earth}}^2}{c^2}\) itself. For the air, where \(N_{\text{air}} \sim 1.00029\), assuming a value \(v_{\text{earth}} \sim 365 \text{ km/s}\), one would expect fringe shifts governed by an effective velocity \(v_{\text{obs}} \sim 8.8 \text{ km/s}\) consistently with our value Eq.(7).

This would also explain why the experiments of Illingworth \[10\] (performed in an apparatus filled with helium where \(N_{\text{helium}} \sim 1.000036\)) and Joos \[11\] (performed in the vacuum where \(N_{\text{vacuum}} \sim 1.000000\)) were showing smaller fringe shifts and, therefore, lower effective velocities.

In Ref.\[12\] the argument has been completely reformulated by using Lorentz transformations (see also Ref.\[13\]). As a matter of fact, in this case there is a non-trivial difference of a factor \(\sqrt{3}\). When properly taken into account, the Earth’s velocity extracted from the absolute magnitude of the fringe shifts is \textit{not} \(v_{\text{earth}} \sim 365 \text{ km/s}\) but \(v_{\text{earth}} \sim 201 \text{ km/s}\) thus making Miller’s prediction Eq.(8) completely consistent with Eq.(7). For the convenience of the reader, we shall report in the following the essential steps.

3. We shall start from the idea that light propagates in a medium with refractive index \(N_{\text{medium}} > 1\) and small Fresnel’s drag coefficient

\[
k_{\text{medium}} = 1 - \frac{1}{N_{\text{medium}}^2} \ll 1
\]

Let us also introduce an isotropical speed of light \((c = 2.9979..10^{10} \text{ cm/s})\)

\[
u \equiv \frac{c}{N_{\text{medium}}}
\]

The basic question is to determine experimentally, and to a high degree of accuracy, whether light propagates isotropically with velocity Eq.(10) for an observer \(S'\) placed on the Earth. For instance for the air, where the relevant value is \(N_{\text{air}} = 1.00029\), the isotropical value \(\frac{c}{N_{\text{air}}}\) is usually determined directly by measuring the two-way speed of light along various directions.
In this way, isotropy can be established at the level $\sim 10^{-7}$. If we require, however, a higher level of accuracy, say $10^{-9}$, the only way to test isotropy is to perform a Michelson-Morley type of experiment and look for fringe shifts upon rotation of the interferometer.

Now, if one finds experimentally fringe shifts (and thus some non-zero anisotropy), one can explore the possibility that this effect is due to the Earth’s motion with respect to a preferred frame $\Sigma \neq S'$. In this perspective, light would propagate isotropically with velocity as in Eq. (10) for $\Sigma$ but not for $S'$.

Assuming this scenario, the degree of anisotropy for $S'$ can easily be determined by using Lorentz transformations. By defining $v$ the velocity of $S'$ with respect to $\Sigma$ one finds

$$u' = \frac{u - \gamma v + v(\gamma - 1) \frac{v \cdot u}{v^2}}{\gamma (1 - \frac{v^2}{c^2})}$$

(11)

where $v = |v|$. By keeping terms up to second order in $v/u$, one obtains

$$\frac{|u'|}{u} = 1 - \alpha \frac{v}{u} - \beta \frac{v^2}{u^2}$$

(12)

where ($\theta$ denotes the angle between $v$ and $u$)

$$\alpha = (1 - \frac{1}{N_{\text{medium}}^2}) \cos \theta + O((N_{\text{medium}}^2 - 1)^2)$$

(13)

$$\beta = (1 - \frac{1}{N_{\text{medium}}^2}) P_2(\cos \theta) + O((N_{\text{medium}}^2 - 1)^2)$$

(14)

with $P_2(\cos \theta) = \frac{1}{2}(3 \cos^2 \theta - 1)$.

Finally defining $u'(\theta) = |u'|$, the two-way speed of light is

$$\frac{u'(\theta)}{u} = \frac{1}{u} \frac{2u'(\pi + \theta)}{u'(\pi + \theta) + u'(\pi + \theta)} = 1 - \frac{v^2}{c^2} (A + B \sin^2 \theta)$$

(15)

where

$$A = N_{\text{medium}}^2 - 1 + O((N_{\text{medium}}^2 - 1)^2)$$

(16)

and

$$B = -\frac{3}{2}(N_{\text{medium}}^2 - 1) + O((N_{\text{medium}}^2 - 1)^2)$$

(17)

To address the theory of the Michelson-Morley interferometer we shall consider two light beams, say 1 and 2, that for simplicity are chosen perpendicular in $\Sigma$ where they propagate along the $x$ and $y$ axis with velocities $u_x(1) = u_y(2) = u = \frac{c}{N_{\text{medium}}}$. Let us also assume that the velocity $v$ of $S'$ is along the $x$ axis.

Let us now define $L'_P$ and $L'_Q$ to be the lengths of two optical paths, say P and Q, as measured in the $S'$ frame. For instance, they can represent the lengths of the arms of an
interferometer which is at rest in the \( S' \) frame. In the first experimental set-up, the arm of length \( L'_P \) is taken along the direction of motion associated with the beam 1 while the arm of length \( L'_Q \) lies along the direction of the beam 2.

In this way, the interference pattern, between the light beam coming out of the optical path \( P \) and that coming out of the optical path \( Q \), can easily be obtained from the relevant delay time. By using the equivalent form of the Robertson-Mansouri-Sexl parametrization \[14, 15\] for the two-way speed of light defined above in Eq.(15), this is given by

\[
\Delta T'(0) = \frac{2L'_P}{w'(0)} - \frac{2L'_Q}{w'(\pi/2)}
\]

(18)

On the other hand, if the beam 2 were to propagate along the optical path \( P \) and the beam 1 along \( Q \), one would obtain a different delay time, namely

\[
(\Delta T')_{\text{rot}} = \frac{2L'_P}{w'(\pi/2)} - \frac{2L'_Q}{w'(0)}
\]

(19)

Therefore, by rotating the apparatus and using Eqs.(16) and (17), one obtains fringe shifts proportional to

\[
\Delta T'(0) - (\Delta T')_{\text{rot}} \sim (-2B) \frac{(L'_P + L'_Q)}{u} \frac{v^2}{u^2}
\]

(20)

or

\[
\Delta T'(0) - (\Delta T')_{\text{rot}} \sim \frac{3(L'_P + L'_Q)}{u} k_{\text{medium}} \frac{v^2}{u^2}
\]

(21)

(neglecting \( O(\kappa_{\text{medium}}^2) \) terms). This coincides with the pre-relativistic expression provided one replaces \( v \) with an effective observable velocity

\[
v_{\text{obs}} = v \sqrt{k_{\text{medium}} \sqrt{3}}
\]

(22)

Finally, for the Michelson-Morley experiment, where \( L'_P = L'_Q = D \), and for an ether wind along the \( x \) axis, the prediction for the fringe shifts at a given angle \( \theta \) has the particularly simple form

\[
\frac{\Delta \lambda(\theta)}{\lambda} = \frac{u \Delta T'(\theta)}{\lambda} = \frac{u}{\lambda} \left( \frac{2D}{w'(\theta)} - \frac{2D}{w'({\pi}/2 + \theta)} \right) = \frac{2D}{\lambda} \frac{v^2}{c^2} (-B) \cos(2\theta)
\]

(23)

that corresponds to a pure second-harmonic effect. At the same time, it becomes clear the remark by Shankland et al. (see page 178 of Ref.[6]) that its amplitude

\[
\bar{A}_2 = \frac{2D}{\lambda} \frac{v^2}{c^2} (-B) = \frac{D v_{\text{obs}}^2}{\lambda} \frac{1}{c^2}
\]

(24)

is just one-half of the corresponding quantity entering Eq.(20).
4. Now, if upon operation of the interferometer there are fringe shifts and if their magnitude, observed with different dielectric media and within the experimental errors, points consistently to a unique value of the Earth’s velocity, there is experimental evidence for the existence of a preferred frame \( \Sigma \neq S' \). In practice, to \( \mathcal{O}(v_\text{earth}^2/c^2) \), this can be decided by re-analyzing \([8]\) the experiments in terms of the effective parameter \( \epsilon = \frac{v_\text{earth}^2}{u_k} \). The conclusion of Cahill and Kitto \([8]\) is that the classical experiments are consistent with the value \( v_\text{earth} \sim 365 \text{ km/s} \) obtained from the COBE data.

However, in our expression Eq.\((22)\) determining the fringe shifts there is a difference of a factor \( \sqrt{3} \) with respect to their result \( v_\text{obs} = v \sqrt{f_\text{medium}} \). Therefore, using Eqs.\((22)\) and \((17)\), for \( N_\text{air} \sim 1.00029 \), the relevant Earth’s velocity (in the plane of the interferometer) is not \( v_\text{earth} \sim 365 \text{ km/s} \) but rather

\[
v_\text{earth} \sim 201 \pm 12 \text{ km/s}
\] (25)

in excellent agreement with the value Eq.\((8)\) calculated by Miller.

Therefore, from this excellent agreement, we deduce that the magnitude of the fringe shifts is determined by the typical velocity of the solar system within our galaxy and not, for instance, by its velocity relatively to the centroid of the Local Group. In the latter case, one would get higher values such as \( v_\text{earth} \sim 336 \text{ km/sec} \), see Ref.\([16]\).

Notice that such ambiguity, say \( v_\text{earth} \sim 200, 300, 365, \ldots \text{ km/s} \), on the actual value of the Earth’s velocity determining the fringe shifts, can only be resolved experimentally in view of the many theoretical uncertainties in the operative definition of the preferred frame where light propagates isotropically. At this stage, we believe, one should just concentrate on the internal consistency of the various frameworks. In this sense, the analysis presented in this paper shows that internal consistency is extremely high in Miller’s 1932 solution.

We are aware that our conclusion goes against the widely spread belief that Miller’s results were only due to statistical fluctuation and/or local temperature conditions (see the Abstract of Ref.\([6]\)). However, within the paper the same authors of Ref.\([6]\) say that "...there can be little doubt that statistical fluctuations alone cannot account for the periodic fringe shifts observed by Miller” (see page 171 of Ref.\([6]\)). In fact, although "...there is obviously considerable scatter in the data at each azimuth position,...the average values...show a marked second harmonic effect” (see page 171 of Ref.\([6]\)). In any case, interpreting the observed effects on the base of the local temperature conditions cannot be the whole story since "...we must admit that a direct and general quantitative correlation between amplitude and phase of the observed second harmonic on the one hand and the thermal conditions in the observation hut on the other hand could not be established” (see page 175 of Ref.\([6]\)). This rather
unsatisfactory explanation of the observed effects should be compared with the previously mentioned excellent agreement that was instead obtained by Miller once the final parameters for the Earth’s velocity were plugged in the theoretical predictions (see Figs. 26 and 27 of Ref. [4]).

This does not exclude the presence of some systematic effect in the Miller’s data. In fact, as mentioned above, Miller’s value $A_2 = 0.044 \pm 0.005$, that perfectly agrees with Eq. (7), was only obtained after the critical re-analysis of Shankland et al. (see page 170 of Ref. [6]).

On the other hand, additional information on the validity of the Miller’s results can also be obtained by other means, for instance comparing with the experiment performed by Michelson, Pease and Pearson [17]. These other authors in 1929, using their own interferometer, again at Mt. Wilson, declared that their ”precautions taken to eliminate effects of temperature and flexure disturbances were effective”. Therefore, their statement that the fringe shift, as derived from ”...the displacements observed at maximum and minimum at sidereal times...”, was definitely smaller than ”...one-fifteenth of that expected on the supposition of an effect due to a motion of the solar system of three hundred kilometres per second”, can be taken as an indirect confirmation of Miller’s results. Indeed, although the ”one-fifteenth” was actually a ”one-fiftieth” (see pag. 240 of Ref. [3]), their fringe shifts were certainly non negligible. This is easily understood since, for an in-air-operating interferometer, the fringe shift $(\Delta \lambda)_{\text{class}}(300)$, expected on the base of classical physics for an Earth’s velocity of 300 km/s, is about 500 times bigger than the corresponding relativistic one

$$(\Delta \lambda)_{\text{rel}}(300) \equiv 3k_{\text{air}} (\Delta \lambda)_{\text{class}}(300) \quad (26)$$

computed using Lorentz transformations (compare with Eqs. (21) and (22) for $k_{\text{air}} \sim N_{\text{air}}^2 - 1 \sim 0.00058$). Therefore, the Michelson-Pease-Pearson upper bound

$$(\Delta \lambda)_{\text{obs}} < 0.02 (\Delta \lambda)_{\text{class}}(300) \quad (27)$$

is actually equivalent to

$$(\Delta \lambda)_{\text{obs}} < 24 (\Delta \lambda)_{\text{rel}}(208) \quad (28)$$

As such, it poses no strong restrictions and is entirely consistent with those typical low effective velocities detected by Miller in his observations of 1925-1926.

A similar agreement is obtained when comparing with the Illingworth’s data [10] as recently re-analyzed by Munera [5]. In this case, using Eq. (22), from the observable velocity $v_{\text{obs}} = 3.13 \pm 1.04 \text{ km/s}$ [5] and the value $N_{\text{helium}} \sim 1.000036$, one deduces $v_{\text{earth}} = 213 \pm 71 \text{ km/s}$, in very good agreement with Eq. (8).

8
The same conclusion applies to the Joos experiment [11]. His interferometer was placed in an evacuated housing and he declared that the velocity of any ether wind had to be smaller than 1.5 km/s. Although we don’t know the exact value of $N_{\text{vacuum}}$ for the Joos experiment, it is clear that this is the type of upper bound expected in this case. As an example, for $v_{\text{earth}} \sim 208$ km/s, one obtains $v_{\text{obs}} \sim 1.5$ km/s for $N_{\text{vacuum}} \sim 1.000009$ and $v_{\text{obs}} \sim 0.5$ km/s for $N_{\text{vacuum}} \sim 1.000001$. In this sense, the effect of using Lorentz transformations is most dramatic for the Joos experiment when comparing with the classical expectation for an Earth’s velocity of 30 km/s. Although the relevant Earth’s velocity is $\sim 208$ km/s, the fringe shifts, rather than being $\sim 50$ times bigger than the classical prediction, are $\sim 1000$ times smaller.

5. We shall conclude with a brief comparison with present-day, ‘vacuum’ Michelson-Morley experiments of the type first performed by Brillet and Hall [18] and more recently by Müller et al. [19]. In a perfect vacuum, by definition $N_{\text{vacuum}} = 1$ so that $v_{\text{obs}} = 0$ and no anisotropy can be detected. However, one can explore [13, 20] the possibility that, even in this case, a very small anisotropy might be due to a refractive index $N_{\text{vacuum}}$ that differs from unity by an infinitesimal amount. In this case, the natural candidate to explain a value $N_{\text{vacuum}} \neq 1$ is gravity. In fact, by using the Equivalence Principle, any freely falling frame $S'$ will locally measure the same speed of light as in an inertial frame in the absence of any gravitational effects. However, if $S'$ carries on board an heavy object this is no longer true. For an observer placed on the Earth, this amounts to insert the Earth’s gravitational potential in the weak-field isotropic approximation to the line element of General Relativity [21]

$$ds^2 = (1 + 2\varphi)dt^2 - (1 - 2\varphi)(dx^2 + dy^2 + dz^2)$$

so that one obtains a refractive index for light propagation

$$N_{\text{vacuum}} \sim 1 - 2\varphi$$

This represents the ‘vacuum’ analogue of $N_{\text{air}}$, $N_{\text{helium}}$,...so that from

$$\varphi = -\frac{G_NM_{\text{earth}}}{c^2 R_{\text{earth}}} \sim -0.7 \cdot 10^{-9}$$

and using Eq.(17) one predicts

$$B_{\text{vacuum}} \sim -4.2 \cdot 10^{-9}$$

For $v_{\text{earth}} \sim 208$ km/s, this implies an observable anisotropy of the two-way speed of light in the vacuum Eq.(15)

$$\frac{\Delta \bar{c}}{c} \sim |B_{\text{vacuum}}| \frac{v_{\text{earth}}^2}{c^2} \sim 2 \cdot 10^{-15}$$
in good agreement with the experimental value \( \Delta \frac{\alpha}{c} = (2.6 \pm 1.7) \cdot 10^{-15} \) determined by Müller et al. [19].

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| SESSION               | $\tilde{A}_2$     |
|-----------------------|-------------------|
| July 8 (noon)         | 0.010 ± 0.005     |
| July 9 (noon)         | 0.015 ± 0.005     |
| July 11 (noon)        | 0.025 ± 0.005     |
| July 8 (evening)      | 0.014 ± 0.005     |
| July 9 (evening)      | 0.011 ± 0.005     |
| July 12 (evening)     | 0.018 ± 0.005     |

Table 1: We report the amplitude of the second-harmonic component $\tilde{A}_2$ obtained from the fit Eq.4 to the various samples of data.