

From classical to modern ether-drift experiments: the narrow window for a preferred frame

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Abstract

Modern ether-drift experiments look for a preferred frame by measuring the difference $\Delta\nu$ in the relative frequencies of two cavity-stabilized lasers, upon local rotations of the apparatus or under the Earth's rotation. If the small deviations observed in the classical ether-drift experiments were not mere instrumental artifacts, by replacing the high vacuum in the resonating cavities with a dielectric gaseous medium (e.g. air), the typical measured $\Delta\nu \sim 1$ Hz should increase *by orders of magnitude*. This prediction is consistent with the characteristic modulation of a few kHz observed in the original experiment with He-Ne masers. However, if such enhancement would not be confirmed by new and more precise data, the existence of a preferred frame can be definitely ruled out.

PACS: 03.30.+p, 01.55.+b

To appear in Physics Letters A

1. The controversy about the existence of a preferred reference frame dates back to the birth of the Theory of Relativity, i.e. to the basic differences between Einstein's Special Relativity [1] and the Lorentz-Poincaré point of view [2, 3]. Today the former interpretation is generally accepted. However, the conceptual relevance of retaining a physical substratum as an important element of the physical theory [4], may induce to re-discover the potentially profound implications of the latter [5, 6]. For instance, replacing the empty space-time of Special Relativity with a preferred frame, one gets a different view of the non local aspects of the quantum theory, see Refs.[7, 8].

Another argument that might induce to re-consider the idea of a preferred frame was given in Ref.[9]. The argument was based on the simultaneous presence of two ingredients that are often found in present-day elementary particle physics, namely: a) vacuum condensation, as with the Higgs field in the electroweak theory, and b) an approximate form of locality, as with cutoff-dependent, effective quantum field theories. In this case, one is faced with 'reentrant violations of special relativity in the low-energy corner' [10]. These are deviations at *small* momenta $|\mathbf{p}| < \delta$ where the infrared scale δ vanishes, in units of the Lorentz-invariant scale M of the theory, only in the local limit of the continuum theory $\frac{\Lambda}{M} \rightarrow \infty$, Λ being the ultraviolet cutoff. A simple interpretation of the phenomenon, in the case of a condensate of spinless quanta, is in terms of density fluctuations of the system [11, 12], the continuum theory corresponding to the incompressibility limit. The resulting picture of the ground state is closer to a medium with a non-trivial refractive index [9] than to the empty space-time of Special Relativity.

Therefore, in the presence of a non-trivial vacuum, it is natural to explore whether the *physically realized* form of the Theory of Relativity is closer to the Einstein's formulation or to the original Lorentzian approach with a preferred frame. In other words, the same relativistic effects between two observers S' and S'' , rather than being due to their *relative* motion, might be interpreted as arising from their *individual* motion with respect to some preferred frame Σ . This equivalence is a simple consequence of the group structure of Lorentz transformations, where the relative velocity parameter β_{rel} connecting S' to S'' can be expressed in terms of the individual velocity parameters β' and β'' respectively relating S' and S'' to Σ as

$$\beta_{\text{rel}} = \frac{\beta' - \beta''}{1 - \beta' \beta''} \quad (1)$$

(we restrict for simplicity to one-dimensional motions).

In this perspective, the crucial question becomes the following: can the individual parameters β' and β'' be determined separately through ether-drift experiments ? Accepting the

standard ‘null-result’ interpretation of this type of experiments, this is not possible. Therefore, if really only β_{rel} is experimentally measurable, one is driven to conclude (as Einstein did in 1905 [1]) that the introduction of a preferred frame is ‘superfluous’, all effects of Σ being re-absorbed into the relative space-time units of any pair (S', S'') .

On the other hand, if the ether-drift experiments give a non-null result, so that β' and β'' can be separately determined, then the situation is completely different. In fact, now β_{rel} is a derived quantity and the Lorentzian point of view is uniquely singled out.

Due to the importance of the problem, we have first re-considered the classical ether-drift experiments, our main motivation being that, according to some authors, their standard null-result interpretation is not so obvious. The fringe shifts observed in the various Michelson-Morley type of experiments, although smaller than the classical predictions, were never really negligibly small. Interpreting these small deviations on the base of Ref.[9], a narrow experimental window might still be compatible with the existence of a preferred frame.

After this first part, we have concentrated our analysis on the modern ether-drift experiments, those where the observation of the interference fringes is replaced by the difference $\Delta\nu$ in the relative frequencies of two cavity-stabilized lasers upon local rotations of the apparatus [13] or under the Earth’s rotation [14]. It turns out that, even in this case, the most recent data [14] leave some space for a non-null interpretation of the experimental results.

For this reason, we shall propose a sharp experimental test that can definitively decide about the existence of a preferred frame. If the small deviations found in the classical experiments were not mere instrumental artifacts, by replacing the high vacuum used in the resonating cavities with a dielectric gaseous medium, the typical frequency of the signal should increase from values $\Delta\nu \sim 1$ Hz up to $\Delta\nu \sim 100$ kHz, using air, or up to $\Delta\nu \sim 10$ kHz, using helium. The latter prediction appears to be consistent with the characteristic modulation of a few kHz in the magnitude of the $\Delta\nu$ ’s observed by Jaseja et al. [15] using He-Ne masers.

2. A non-null result of the original Michelson-Morley [16] experiment was strongly advocated by Hicks [17] long time ago. The same conclusion was obtained by Miller after his re-analysis of the Michelson-Morley data, of the Morley-Miller [18] experiments and of his own measurements at Mt.Wilson, see Fig.4 of Ref.[19]. Miller’s refined analysis showed that all data were consistent with an effective, *observable* velocity lying in the range 7-10 km/s, say

$$v_{\text{obs}} \sim 8.5 \pm 1.5 \text{ km/s} \tag{2}$$

For comparison, the Michelson-Morley experiment gave a value $v_{\text{obs}} \sim 8.8$ km/s for the noon observations and a value $v_{\text{obs}} \sim 8.0$ km/s for the evening observations. As the fringe shifts grow quadratically with the velocity, their typical magnitude was $(8.5/30)^2 \sim 1/13$ of that expected, on the base of classical physics, for the Earth’s orbital velocity of 30 km/s.

The difference of the value in Eq.(2) with respect to the original conclusion of Michelson-Morley (v_{obs} certainly smaller than 1/4 of the Earth’s orbital velocity [16]), can partly be understood looking at the conclusions of the Hicks’ study [17]: one is not allowed to average data of different experimental sessions unless one is sure that the direction of the ether-drift effect remains the same (see page 34 of [17] “It follows that averaging the results of different days in the usual manner is not allowable...If this is not attended to, the average displacement may be expected to come out zero...”). In other words, the ether-drift, if it exists, has a vectorial nature. Therefore, rather than averaging the raw data from the various sessions, one should first consider the data from the i -th experimental session and extract the observable velocity $v_{\text{obs}}(i)$ and the ether-drift direction $\theta_o(i)$ for that session. Finally, a mean magnitude $\langle v_{\text{obs}} \rangle$ and a mean direction $\langle \theta_o \rangle$ can be obtained by averaging the individual determinations (see Figs. 22 of Ref.[19]).

Now, following the latter strategy, the magnitude of the observable velocity comes out to be larger, its error becomes smaller so that the evidence for an ether-drift effect becomes stronger (see page 36 of Ref.[17] “...this naturally leads to the reconsideration of the numerical data obtained by Michelson and Morley, who did lump together the observations taken in different days. I propose to show that, instead of giving a null result, the numerical data published in their paper show distinct evidence of an effect of the kind to be expected”).

The same was true for the Morley-Miller data [18]. In this case, the morning and evening observations each were indicating an effective velocity of about 7.5 km/s (see Fig.11 of Ref.[19]). This indication was completely lost after averaging the raw data as in Ref.[18]. Finally, the same point of view has been advocated by Múnera in his recent re-analysis of the classical experiments [20].

3. Now, suppose we accept the value in Eq.(2) to summarize the results of the Michelson-Morley, Morley-Miller and Miller experiments. As these were performed in air, it would mean that the measured two-way speed of light differs from an exactly isotropical value

$$u_{\text{air}} = \frac{c}{\mathcal{N}_{\text{air}}} \tag{3}$$

\mathcal{N}_{air} denoting the refractive index of the air. Namely, for an observer placed on the Earth

(where the air is at rest or more precisely in thermodynamical equilibrium) the experiments say that there is a small anisotropy at the level $\mathcal{O}(\frac{v_{\text{obs}}^2}{c^2}) \sim 10^{-9}$ so that the isotropical value Eq.(3) is only accurate at a lower level of accuracy, say $\sim 10^{-8}$.

On the other hand, for the Kennedy's [21] experiment, where the whole optical system was inclosed in a sealed metal case containing helium at atmospheric pressure, the observed anisotropy was definitely smaller. In fact, the accuracy of the experiment, such to exclude fringe shifts as large as 1/4 of those expected on the base of Eq.(2) (or 1/50 of that expected on the base of a velocity of 30 km/s) allows to place an upper bound $v_{\text{obs}} < 4$ km/s. This is confirmed by the re-analysis of the Illingworth's experiment [22] performed by Mùnera [20] who pointed out some incorrect assumptions in the original analysis of the data. From this re-analysis, the relevant observable velocity turns out to be $v_{\text{obs}} = 3.1 \pm 1.0$ km/s (errors at the 95% C.L.) [20], with typical fringe shifts that were 1/100 of that expected for a velocity of 30 km/s. Again, this means that, for an apparatus filled with gaseous helium at atmospheric pressure, the measured two-way speed of light differs from the exactly isotropical value $\frac{c}{\mathcal{N}_{\text{helium}}}$ by terms $\mathcal{O}(\frac{v_{\text{obs}}^2}{c^2}) \sim 10^{-10}$.

Finally, for the Joos experiment [23], performed in an evacuated housing and where any ether-wind was found smaller than 1.5 km/s, the typical value $v_{\text{obs}} \sim 1$ km/s means that, in that particular type of vacuum, the fringe shifts were smaller than 1/400 of those expected for an Earth's velocity of 30 km/s and the anisotropy of the two-way speed of light was at the level $\sim 10^{-11}$.

We shall try to summarize the above experimental results as follows. When light propagates in a gaseous medium, the exactly isotropical value

$$u = \frac{c}{\mathcal{N}_{\text{medium}}} \tag{4}$$

holds approximately for an observer placed on the Earth. Within the context of a Theory of Relativity with a preferred frame, this should not come as a complete surprise. In fact, the usual assumption, that the isotropical value Eq.(4) holds exactly in the reference frame S' where the gas is in thermodynamical equilibrium, reflects the point of view of Special Relativity with no preferred frame. However, to *test* this assumption requires precisely to perform a Michelson-Morley experiment and look for fringe shifts upon local rotations of the apparatus.

When this is done, the experiments indicate a slight anisotropy that becomes smaller when the refractive index of the medium approaches unity. In fact v_{obs} , and thus the anisotropy, is larger for those interferometers operating in air, where $\mathcal{N}_{\text{air}} \sim 1.00029$, and becomes smaller

in experiments performed in helium, where $\mathcal{N}_{\text{helium}} \sim 1.000036$, or in an evacuated housing. This is completely consistent with the expectations based on Lorentz transformations that preserve the isotropical value of the speed of light in the vacuum $c = 2.9979... \cdot 10^{10}$ cm/s. If these are valid, even in the presence of a preferred frame, no anisotropy can be detected studying light propagation in the vacuum where $\mathcal{N}_{\text{vacuum}} = 1$ identically.

However, Lorentz transformations do not preserve the value of the speed of light in a medium. Therefore, the simplest way to generate an anisotropy in S' is to start from the isotropical value Eq.(4), assumed to be valid in some preferred frame Σ , and compute its value in S' through a Lorentz transformation.

Notice that this series of steps is completely analogous to the conventional treatment of the Michelson-Morley experiment. There, one starts from the isotropical value c in Σ and uses Galileian relativity (for which the speed of light becomes $c \pm v$) to transform to the observer S' placed in the Earth's frame. Here we shall only take into account that i) light propagates in a gaseous medium and ii) Galilei's transformations have to be replaced by Lorentz transformations.

There is, however, a hidden assumption in our procedure that should be clearly spelled out. Eq.(4) is strictly valid for a medium at rest in the preferred frame Σ . However, the medium is at rest in S' and not in Σ . Therefore, strictly speaking, before Lorentz transforming to S' , we should first correct the Σ estimate for the effect of the Fresnel's drag that might exist anyway. Of course, if we had to use the exact relativistic formula to compute this effect and then transform to S' , we would obtain that the isotropical value Eq.(4) holds in S' as well. Here, following the experimental indications of a non-zero anisotropy in S' , we shall assume that the Fresnel's drag for Σ is negligible, at least for gaseous media, so that the anisotropy in S' is due to the genuine Lorentz transformation. This assumption reflects the point of view that, if there is really a preferred frame, there must be somewhere a basic asymmetry between Σ and S' . We stress, however, that our assumption of a negligible Fresnel's drag in Σ cannot be extended to light propagation in solid dielectrics with high refractive index. In fact, Michelson-Morley experiments performed in a solid transparent medium (perspex) [24], where $\mathcal{N}_{\text{perspex}} \sim 1.5$, show no anisotropy.

The peculiar role of gaseous media can partly be understood noticing that they cover the ideal limit where the refractive index \mathcal{N} tends to unity. For $\mathcal{N} = 1$, light is seen to propagate isotropically in the hypothetical preferred frame and in all moving frames S' , S'' , S''' ,... For $\mathcal{N} \neq 1$, however, light has to resolve this infinite 'degeneracy' and necessarily choose between two different alternatives: either to propagate isotropically in the rest frame of the medium

or in Σ . The experiments suggest that for $(\mathcal{N} - 1) \ll 1$ there might be still no Fresnel's drag for Σ so that light is seen to propagate isotropically in Σ and not in S' . However, when \mathcal{N} starts to differ sizeably from unity, the Fresnel's drag in Σ becomes substantial so as to cancel the effect of the genuine Lorentz transformation to S' . In this new regime, light propagates isotropically in the rest frame of the medium. Just for this reason, experiments performed in gaseous media represent the only remaining window to detect the possible existence of a preferred frame.

Within the above assumptions, starting from Eq.(4) and denoting by \mathbf{v} the velocity of S' with respect to Σ , a Lorentz transformation give the general expression for the one-way speed of light in S' ($\gamma = 1/\sqrt{1 - \frac{v^2}{c^2}}$)

$$\mathbf{u}' = \frac{\mathbf{u} - \gamma\mathbf{v} + \mathbf{v}(\gamma - 1)\frac{\mathbf{v}\cdot\mathbf{u}}{v^2}}{\gamma(1 - \frac{\mathbf{v}\cdot\mathbf{u}}{c^2})} \quad (5)$$

where $v = |\mathbf{v}|$. By keeping terms up to second order in v/u , denoting by θ the angle between \mathbf{v} and \mathbf{u} and defining $u'(\theta) = |\mathbf{u}'|$, we obtain

$$\frac{u'(\theta)}{u} = 1 - \alpha\frac{v}{u} - \beta\frac{v^2}{u^2} \quad (6)$$

where

$$\alpha = k_{\text{medium}} \cos \theta + \mathcal{O}(k_{\text{medium}}^2) \quad (7)$$

$$\beta = k_{\text{medium}} P_2(\cos \theta) + \mathcal{O}(k_{\text{medium}}^2) \quad (8)$$

with

$$k_{\text{medium}} = 1 - \frac{1}{\mathcal{N}_{\text{medium}}^2} \ll 1 \quad (9)$$

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

Finally, the two-way speed of light is

$$\frac{\bar{u}'(\theta)}{u} = \frac{1}{u} \frac{2u'(\theta)u'(\pi + \theta)}{u'(\theta) + u'(\pi + \theta)} = 1 - \frac{v^2}{c^2}(A + B \sin^2 \theta) \quad (10)$$

where

$$A = k_{\text{medium}} + \mathcal{O}(k_{\text{medium}}^2) \quad (11)$$

and

$$B = -\frac{3}{2}k_{\text{medium}} + \mathcal{O}(k_{\text{medium}}^2) \quad (12)$$

In this way, as shown in Ref.[9], one obtains formally the same pre-relativistic expressions where the kinematical velocity v is replaced by an effective observable velocity

$$v_{\text{obs}} = v\sqrt{k_{\text{medium}}}\sqrt{3} \sim v\sqrt{-2B} \quad (13)$$

For instance, for the Michelson-Morley experiment, and for an ether wind along the x axis, the prediction for the fringe shifts at a given angle θ with the x axis has the particularly simple form (D being the length of each arm of the interferometer as measured in S')

$$\frac{\Delta\lambda(\theta)}{\lambda} = \frac{u}{\lambda} \left(\frac{2D}{u'(\theta)} - \frac{2D}{u'(\pi/2 + \theta)} \right) \sim \frac{D}{\lambda} \frac{v^2}{c^2} (-2B) \cos(2\theta) = \frac{D}{\lambda} \frac{v_{\text{obs}}^2}{c^2} \cos(2\theta) \quad (14)$$

that corresponds to a pure second-harmonic effect as in the old theory (see for instance Refs.[17, 25]) where v^2 is replaced by v_{obs}^2 . Notice that, in agreement with the basic isotropy of space, embodied in the validity of Lorentz transformations, the measured length of an interferometer at rest in S' is D regardless of its orientation.

Also, the trend predicted by Eqs.(13) and (14), where the observable velocity, and thus the anisotropy, becomes smaller and smaller when $\mathcal{N}_{\text{medium}}$ approaches unity, is consistent with the analysis of the experiments performed by Kennedy, Illingworth and Joos vs. those of Michelson-Morley, Morley-Miller and Miller. We note that a qualitatively similar suppression effect had already been discovered by Cahill and Kitto [26] by following a different approach.

4. As stressed in Ref.[9], the detection of a preferred frame in ether-drift experiments is a purely experimental issue. Within our assumptions, this requires: i) the preliminary observation of fringe shifts upon operation of the interferometer and ii) that their magnitude, observed with different gaseous media and within the experimental errors, points consistently to a unique value of the kinematical Earth's velocity. Only in this case, one can conclude that there is experimental evidence for the existence of a preferred frame.

To extract the value of the kinematical Earth's velocity corresponding to the various v_{obs} , one should re-analyze the experiments in terms of the effective parameter $\epsilon = \frac{v_{\text{earth}}^2}{u^2} k_{\text{medium}}$. The conclusion of Cahill and Kitto [26] is that the classical experiments are consistent with the value $v_{\text{earth}} \sim 365$ km/s obtained from the dipole fit to the COBE data [27] for the cosmic background radiation. However, in our expression Eq.(13) determining the fringe shifts there is a difference of a factor $\sqrt{3}$ with respect to their result $v_{\text{obs}} = v\sqrt{k_{\text{medium}}}$. Therefore, using Eqs.(13) and (2), for $\mathcal{N}_{\text{air}} \sim 1.00029$, the relevant Earth's velocity (in the plane of the interferometer) is *not* $v_{\text{earth}} \sim 365$ km/s but rather

$$v_{\text{earth}} \sim 204 \pm 36 \text{ km/s} \quad (15)$$

In this way, using our Eq.(13), the kinematical Earth's velocity becomes consistent with the values needed by Miller to understand the *variations* of the ether-drift effect in different epochs of the year [19]. In fact, the typical daily values, in the plane of the interferometer,

had to lie in the range $195 \leq v_{\text{earth}} \leq 211$ km/s (see Table V of Ref.[19]). Such a consistency, on one hand, increases the body of experimental evidence for a preferred frame, and on the other hand, provides a definite range of velocities to be used in the analysis of the other experiments.

To this end, let us compare with the experiment performed by Michelson, Pease and Pearson [28]. 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 our Eq.(15). Indeed, although the “one-fifteenth” was actually a “one-fiftieth” (see page 240 of Ref.[19]), 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

$$(\Delta\lambda)_{\text{rel}}(300) \equiv 3k_{\text{air}} (\Delta\lambda)_{\text{class}}(300) \quad (16)$$

computed using Lorentz transformations (compare with Eq.(14) for $k_{\text{air}} \sim \mathcal{N}_{\text{air}}^2 - 1 \sim 0.00058$). Therefore, the Michelson-Pease-Pearson upper bound

$$(\Delta\lambda)_{\text{obs}} < 0.02 (\Delta\lambda)_{\text{class}}(300) \quad (17)$$

is actually equivalent to

$$(\Delta\lambda)_{\text{obs}} < 24 (\Delta\lambda)_{\text{rel}}(204) \quad (18)$$

As such, it poses no strong restrictions and is entirely consistent with those typical low observable velocities reported in Eq.(2).

A similar agreement is obtained when comparing with the Illingworth’s data [22] as recently re-analyzed by Múnica [20]. In this case, using Eq.(13), the observable velocity $v_{\text{obs}} = 3.1 \pm 1.0$ km/s [20] (errors at the 95% C.L.) and the value $\mathcal{N}_{\text{helium}} - 1 \sim 3.6 \cdot 10^{-5}$, one deduces $v_{\text{earth}} = 213 \pm 36$ km/s (errors at the 68% C.L.) in very good agreement with our Eq.(15).

The same conclusion applies to the Joos experiment [23]. Although we don’t know the exact value of $\mathcal{N}_{\text{vacuum}}$ for the Joos experiment, it is clear that his result, $v_{\text{obs}} < 1.5$ km/s,

represents the natural type of upper bound in this case. As an example, for $v_{\text{earth}} \sim 204$ km/s, one obtains $v_{\text{obs}} \sim 1.5$ km/s for $\mathcal{N}_{\text{vacuum}} - 1 = 9 \cdot 10^{-6}$ and $v_{\text{obs}} \sim 0.5$ km/s for $\mathcal{N}_{\text{vacuum}} - 1 = 1 \cdot 10^{-6}$. 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 can be as large as 204 km/s, the fringe shifts, rather than being $(204/30)^2 \sim 50$ times *bigger* than the classical prediction, are $\sim (30/1.5)^2 = 400$ times *smaller*.

5. Let us finally consider those present-day, 'high vacuum' Michelson-Morley experiments of the type first performed by Brillet and Hall [13] and more recently by Müller et al. [14]. In these experiments, the test of the isotropy of the speed of light does not consist in the observation of the interference fringes as in the classical experiments. Rather, one looks for the difference $\Delta\nu$ in the relative frequencies of two cavity-stabilized lasers upon local rotations of the apparatus [13] or under the Earth's rotation [14].

The present experimental value for the anisotropy of the two-way speed of light in the vacuum, as determined by Müller et al.[14],

$$\frac{\Delta\nu}{\nu} = \left(\frac{\Delta\bar{c}_\theta}{c}\right)_{\text{exp}} = (2.6 \pm 1.7) \cdot 10^{-15} \quad (19)$$

can be interpreted within the framework of our Eq.(10) where

$$\left(\frac{\Delta\bar{c}_\theta}{c}\right)_{\text{theor}} \sim |B_{\text{vacuum}}| \frac{v_{\text{earth}}^2}{c^2} \quad (20)$$

Now, in a perfect vacuum by definition $\mathcal{N}_{\text{vacuum}} = 1$ so that B_{vacuum} and v_{obs} vanish. However, one can explore [9] the possibility that, even in this case, a very small anisotropy might be due to a refractive index $\mathcal{N}_{\text{vacuum}}$ that differs from unity by an infinitesimal amount. In this case, the natural candidate to explain a value $\mathcal{N}_{\text{vacuum}} \neq 1$ is gravity. In fact, by using the Equivalence Principle, a 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 [29]

$$ds^2 = (1 + 2\varphi)dt^2 - (1 - 2\varphi)(dx^2 + dy^2 + dz^2) \quad (21)$$

so that one obtains a refractive index for light propagation

$$\mathcal{N}_{\text{vacuum}} \sim 1 - 2\varphi \quad (22)$$

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

$$\varphi = -\frac{G_N M_{\text{earth}}}{c^2 R_{\text{earth}}} \sim -0.7 \cdot 10^{-9} \quad (23)$$

and using Eq.(12) one predicts

$$B_{\text{vacuum}} \sim -4.2 \cdot 10^{-9} \quad (24)$$

Adopting the range of Earth’s velocity (in the plane of the interferometer) given in Eq.(15) this leads to predict an observable anisotropy of the two-way speed of light in the vacuum Eq.(10)

$$\left(\frac{\Delta \bar{c}_\theta}{c}\right)_{\text{theor}} \sim |B_{\text{vacuum}}| \frac{v_{\text{earth}}^2}{c^2} \sim (1.9 \pm 0.7) \cdot 10^{-15} \quad (25)$$

consistently with the experimental value in Eq.(19).

Clearly, in this framework, trying to rule out the existence of a preferred frame through the experimental determination of $\frac{\Delta \bar{c}_\theta}{c}$ in a high vacuum is not the most convenient strategy due to the vanishingly small value of B_{vacuum} . For this reason, a more efficient search might be performed in dielectric gaseous media. As a check, we have compared with the only available results obtained by Jaseja et. al [15] in 1963 when looking at the relative frequency shifts of two orthogonal He-Ne masers placed on a rotating platform. As we shall show in the following, their data are consistent with the same type of conclusion obtained from the classical experiments: an ether-drift effect determined by an Earth’s velocity as in Eq.(15).

To use the experimental results reported by Jaseja et al.[15] one has to subtract preliminarily a large overall systematic effect that was present in their data and interpreted by the authors as probably due to magnetostriction in the Invar spacers induced by the Earth’s magnetic field. As suggested by the same authors, this spurious effect, that was only affecting the normalization of the experimental $\Delta\nu$, can be subtracted looking at the variations of the data at different hours of the day. The data for $\Delta\nu$, in fact, in spite of their rather large errors, exhibit a characteristic modulation (see Fig.3 of Ref.[15]) with a maximum at about 7:30 a.m. and a minimum at about 9:00 a.m. and a typical difference [15]

$$\delta(\Delta\nu) \sim (1.6 \pm 1.2) \text{ kHz} \quad (26)$$

Our theoretical starting point to understand the above (rather loose) determination is the formula for the frequency shift of the two masers at an angle θ with the direction of the ether-drift

$$\frac{\Delta\nu(\theta)}{\nu} = \frac{\bar{u}'(\pi/2 + \theta) - \bar{u}'(\theta)}{u} = |B_{\text{He-Ne}}| \frac{v_{\text{earth}}^2}{c^2} \cos(2\theta) \quad (27)$$

where, taking into account the values $\mathcal{N}_{\text{helium}} \sim 1.000036$, $\mathcal{N}_{\text{neon}} \sim 1.000067$, $\mathcal{N}_{\text{He-Ne}} \sim 1.00004$ and Eq.(12) we shall use $|B_{\text{He-Ne}}| \sim 1.2 \cdot 10^{-4}$.

Further, using the value of the frequency of Ref.[15] $\nu \sim 3 \cdot 10^{14}$ Hz and our standard value Eq.(15) for the Earth's velocity in the plane of the interferometer $v_{\text{earth}} \sim 200$ km/s, Eq.(27) leads to the reference value for the amplitude of the signal

$$(\Delta\nu)_{\text{ref}} = \nu |B_{\text{He-Ne}}| \frac{(200 \text{ km/s})^2}{c^2} \sim 16 \text{ kHz} \quad (28)$$

and to its time modulation

$$\delta(\Delta\nu)_{\text{theor}} \sim 16 \text{ kHz} \frac{\delta v^2}{v^2} \quad (29)$$

where

$$\frac{\delta v^2}{v^2} \equiv \frac{v_{\text{earth}}^2(7:30 \text{ a.m.}) - v_{\text{earth}}^2(9:00 \text{ a.m.})}{(200 \text{ km/s})^2} \quad (30)$$

To evaluate the above ratio of velocities, let us first compare the modulation of $\Delta\nu$ seen in fig.3 of ref.[15] with that of v_{obs} in fig.27 of ref.[19] (data plotted as a function of civil time as in ref.[15]) restricting to the Miller's data of February, the period of the year that is closer to the date of January 20th when Jaseja *et al.* performed their experiment. Further, the different location of the two laboratories (Mt.Wilson and Boston) can be taken into account with a shift of about three hours so that Miller's interval 3:00 a.m.–9:00 a.m. is made to correspond to the range 6:00 a.m.–12:00 a.m. of Jaseja *et al.*. If this is done, although one does not expect an exact correspondence due to the difference between the two epochs of the year, the two characteristic trends are surprisingly close.

Thus we shall try to use the Miller's data for a rough evaluation of the ratio reported in Eq.(30). In this case, rescaling from v_{obs} to v_{earth} through Eq.(13) (for the Miller's interferometer that was operating in air), we obtain values of $\frac{\delta v^2}{v^2}$ in the range 0.1 – 0.2. This estimate, when replaced in Eq.(29) leads to values of $\delta(\Delta\nu)_{\text{theor}}$ in the range 1.6 – 3.2 kHz, well consistent with the value 1.6 ± 1.2 kHz given in Eq.(26). Of course, one needs more precise data. However, in spite of our crude approximations, the order of magnitude of the effect is correctly reproduced.

This suggests, once more [9], to perform a new class of ether-drift experiments in dielectric gaseous media. For instance, using stabilizing cavities as in Refs.[13, 14], one could replace the high vacuum in the Fabry-Perot with air. In this case, where $|B_{\text{vacuum}}| \sim 4 \cdot 10^{-9}$ would be replaced by $|B_{\text{air}}| \sim 9 \cdot 10^{-4}$, there should be an increase by five orders of magnitude in the typical value of $\Delta\nu$ with respect to Refs.[13, 14].

6. In this Letter we have re-considered the possible existence of a preferred reference frame through an analysis of both classical and modern ether-drift experiments. The small observed velocities $v_{\text{obs}} \sim 8.5 \pm 1.5$ km/s for the Michelson-Morley, Morley-Miller and Miller experiments, $v_{\text{obs}} \sim 3.1 \pm 1.0$ km/s for the Illingworth experiment, and $v_{\text{obs}} \sim 1$ km/s for the Joos experiment, when corrected for the effect of the refractive index, appear to point consistently to a rather large kinematical Earth's velocity $v_{\text{earth}} \sim 204 \pm 36$ km/s (in the plane of the interferometer).

Therefore, it becomes natural to explore the existence of a preferred frame and formulate definite predictions for the relative frequency shift $\Delta\nu$ which is measured in the present-day experiments with cavity-stabilized lasers, upon local rotation of the apparatus or under the Earth's rotation. In this case, our basic relation is

$$\frac{\Delta\nu}{\nu} \sim |B_{\text{medium}}| \frac{v_{\text{earth}}^2}{c^2} \quad (31)$$

where $B_{\text{medium}} \sim -3(\mathcal{N}_{\text{medium}} - 1)$, $\mathcal{N}_{\text{medium}}$ being the refractive index of the gaseous dielectric medium that fills the cavities. For a very high vacuum, using the prediction of General Relativity $|B_{\text{vacuum}}| \sim 4 \cdot 10^{-9}$, and the range of kinematical Earth's velocity $v_{\text{earth}} \sim 204 \pm 36$ km/s suggested by the classical ether-drift experiments, we predict $\frac{\Delta\nu}{\nu} \sim (1.9 \pm 0.7) \cdot 10^{-15}$, consistently with the experimental result of Ref.[14]. For He-Ne masers, the same range of Earth's velocities leads to predict a typical value $\Delta\nu \sim 16$ kHz, for which $\frac{\Delta\nu}{\nu} \sim 5 \cdot 10^{-11}$, with a characteristic modulation of a few kHz in the period of the year and for the hours of the day when Jaseja et al.[15] performed their experiment. This prediction is consistent with their data, although the rather large experimental errors require further experimental checks. For this reason, we propose to replace the high vacuum adopted in the Fabry-Perot cavities with air. In this case, where the anisotropy parameter $|B_{\text{vacuum}}| \sim 4 \cdot 10^{-9}$ would be replaced by $|B_{\text{air}}| \sim 9 \cdot 10^{-4}$, there should be an increase by *five orders of magnitude* in the typical value of $\Delta\nu$ with respect to Refs.[13, 14]. If this is not observed, the existence of a preferred frame will be definitely ruled out.

Acknowledgements

We thank L. Pappalardo for many useful discussions.

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