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THE NEW FORMULA FOR THE SPEED OF LIGHT THROUGH A MOVING OPTICAL MEDIUM: ANOTHER CLASSICAL DERIVATION AND SOME CONSEQUENCES

A. NEAGU [1,*] , I. GORGOS [2,*]

[1] Physicist, retired, Curtea de Arges, Romania

[2] Ionut Gorgos, National University of Science and Technology POLITEHNICA Bucharest

[*] Corresponding authors: *E-mail: nalecxandru@yahoo.com, Tel : +40747499365*
E-mail: ionut.gorgos@upb.ro

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Abstract. In a previous paper [1], a method for determining the new formula for the speed of light through a moving optical medium was presented. The method used was based on determining the length of the optical path traveled by light, when it propagates over a distance L, in the laboratory reference system (LRS), through an optical medium moving at a speed v relative to it. In this paper, the method used to determine the new formula for the speed of light through a moving optical medium is similar to that used in [1], but by approaching the phenomenology of light propagation through an optical medium in more depth, in this case, the length of the optical path was determined taking into account the change, relative to the LRS, of the refractive index of the moving optical medium, in its direction of movement.

Key words: Speed of light, Moving medium, Delay time, Number of particles per unit length, Refractive index of the moving medium.

1. INTRODUCTION

In the early 18th century, the English astronomer James Bradley discovered that the apparent position of a star, observed over the course of a year, changes as a result of the permanent change in the direction of the Earth's orbital velocity [2].

This phenomenon was called *stellar aberration* and played an important role in the evolution of ideas regarding the propagation of light through moving optical media, due to the constraints imposed on various theoretical models, developed to explain the results of some famous experiments in the field.

In the early 19th century, Pierre Simon Laplace, a proponent of the corpuscular theory of light, asked Francois Arago to experimentally verify the dependence of the speed of stellar light reaching Earth on the massiveness of the stars emitting the light and on the orbital motion of the Earth.

Arago accepted Laplace's proposal and in 1810 verified the requirements formulated by him through an experiment that consisted of measuring the angle of refraction of starlight as it passed through an optical prism attached to the eyepiece of a telescope [3]. Contrary to the expectations of the followers of the corpuscular theory of light, Arago did not detect any notable change in the angle of refraction, either in the case of light coming from various stars or in response to changes in the direction of the Earth's orbital velocity. Unable to explain the null result of his experiment within the corpuscular theory of light, Arago asked Jean Augustin Fresnel to explain it within the wave theory of light.

After a period in which it was eclipsed by the corpuscular theory of light, the wave theory of light was revived in the early years of the 19th century, following the discovery of the phenomenon of light interference by the English physician Thomas Young. To explain the propagation of light through space, Young postulated the existence of a material medium called the luminiferous ether, present throughout the universe and having several properties, one of which was its non-entrainment by bodies moving through it [4].

In 1818, Fresnel managed to explain the null result of Arago's experiment within a new model of ether, called the partially entrained ether model [5]. According to this ether model, the speed of light when propagating through an optical medium that moves with speed $\vec{v}$ relative to the stationary ether, in the sense of light propagating through it, is:

$$c' = \frac{c}{n} + v(1 - \frac{1}{n^2}) = \frac{c}{n} + f \cdot v \qquad (1)$$

Relation (1) was called Fresnel's formula for the speed of light through a moving optical medium and the factor f was called Fresnel's entrainment coefficient. Many scientists of the time criticized the way Fresnel derived his formula, and in a paper published in 1872, Mascart even called on theorists to find other explanations for Fresnel's formula or for a slightly different one [6].

Fresnel's partially entrained ether model received significant support following Fizeau's experiment of 1851 [7]. Comparing the results of his experiment with the theoretical predictions of several existing ether models at that time, Fizeau concluded that Fresnel's partially entrained ether hypothesis seemed to provide a suitable theoretical explanation for the results of his experiment, but, hesitantly, he requested that "*before it can be accepted as the expression of the real state of things, additional proofs will be demanded for the physicist as well as a thorough examination of the subject from the mathematician*".

After the emergence of Maxwell's theory of electromagnetism, Lorentz proposed replacing Young's mechanical ether with an electromagnetic ether, weightless and totally immobile, whose only property remained that of allowing the propagation of electromagnetic waves. But the null result of the Michelson-Morley experiment of 1887 [8], caused Lorentz to abandon this ether model.

In his 1905 paper [9], Albert Einstein showed that, since none of the experiments carried out up to that point had succeeded in detecting the motion of material bodies relative to the ether, its use in explaining optical and electrodynamic phenomena was unnecessary, and consequently the ether must be eliminated. In addition, within the theory of relativity, Fresnel's formula results from the direct application of the relativistic velocity composition rule, neglecting terms of order 1 and greater than 1 of the v/c ratio:

$$c' = \frac{c/n + v}{1 + \frac{c/n \cdot v}{c^2}} = \frac{c/n + v}{1 + \frac{v}{nc}} = (\frac{c}{n} + v)(1 - \frac{v}{nc}) \cong \frac{c}{n} + v(1 - \frac{1}{n^2}) \qquad (2)$$

Although after 1905 physical models based on the existence of the ether gradually disappeared from physics, there are still scientists who try to solve various problems of modern physics by taking into account the existence of the ether.

One of these models is the "time-delay" model of Italian scientists Giuseppe Antoni and Umberto Bartocci [10]. Applying this model to the Fizeau experiment, the two Italians also arrived at Fresnel's formula, in a classical way, considering that *"the ether is not dragged at all by the moving water, and that the only physical phenomenon we are dealing with in this case is that the light, during its travel through the moving water (say for a time* Δt*) simple meets fewer obstacles, and that the single delay for each obstacle is (for instance in the case of water moving in the same direction as the light) less than (3)".*

Due to its success in explaining some famous experiments (Arago, Fizeau, Hoek, Airy) and as a result of its derivation within various theoretical models, both classical and relativistic, Fresnel's formula has become the most accepted and practically the only formula experimentally verified, that expresses the speed of light through a moving optical medium.

In a paper published in 2025 [1], we developed a new classical model for the propagation of light through a moving optical medium, which was called the "delay-time" model. Within it, a new formula for the speed of light through a moving optical medium was derived. As we have shown in [1] and [11], this formula also verifies the results of the Fizeau experiment very well.

2. THE "DELAY-TIME" MODEL

The "delay-time" model was developed starting from the "time-delay" model of Italian scientists Giuseppe Antoni and Umberto Bartocci. It is a classical, phenomenological model, which is based on Galilean mechanics and the laws of geometric and wave optics. In order for the theoretical predictions obtained within the delay-time model to be relevant when compared with experimental results, all physical quantities involved in the demonstrations will be expressed or determined in the reference system in which the measurements are made, which we called the laboratory reference system (LRS). The main characteristics of the delay-time model are:

- it does not take into account the existence of ether as a supporting medium for the propagation of electromagnetic waves;
- admits that the light emitted by a light source, at rest or moving with speed v relative to the LRS, propagates through vacuum with speed c relative to it;
- considers that the difference between the time in which light propagates over a certain distance through an optical medium at rest, compared to the time in which light propagates over the same distance in a vacuum, occurs as a result of an electromagnetic interaction between the photons of the light beam and the particles of that optical medium. The macroscopic quantity whose value has a direct relationship with the type and magnitude of the photon-matter interaction, is the refractive index, n, of the respective optical medium;
- considers that the change in the speed of light when it propagates through a moving optical medium, compared to its speed when it propagates through the same medium, at rest with respect to the LRS, is mainly caused by the change in the number of particles of the optical medium overcome by light per unit length.

According to the delay-time model [1], the speed of light through a moving optical medium is given by the relationship:

$$c_{\pm} = \frac{c}{n} \pm 2v\left(1 - \frac{1}{n}\right) \tag{3}$$

In this relationship, c_+ is the speed of light relative to the LRS, when it propagates through the optical medium in the direction of its velocity $\vec{v}$ relative to the LRS, and c_- is the speed of light relative to the LRS, when it propagates in the opposite direction to the velocity $\vec{v}$ of the optical medium.

Relation (3) was called the new formula for the speed of light through a moving optical medium because, like Fresnel's formula, it verifies the results of Fizeau-type experiments very well.

In [1], the new formula for the speed of light through a moving optical medium was deduced by a method that was based on determining the length of the optical path traveled by light, when propagating over a distance L from the LRS, through an optical medium moving with a velocity $\vec{v}$ relative to it.

In this paper, it was derived using a method similar to that used in [1], but this time taking into account the change in the refractive index of the medium through which light propagates, as a result of the change in the number of particles per unit length with which a photon interacts, when it propagates in the direction of movement of the respective optical medium.

3. ANOTHER CLASSICAL DERIVATION OF THE NEW FORMULA FOR THE SPEED OF LIGHT THROUGH A MOVING OPTICAL MEDIUM

We consider that through a tube of length L, at rest in the laboratory reference system, a homogeneous optical medium (water) circulates with constant velocity $\vec{v}$. We also consider that a cylindrical beam of monochromatic light, coming from a light source, at rest with respect to the LRS, propagates through the water in the tube in the direction of its velocity $\vec{v}$. The refractive index of water at rest in the LRS, corresponding to the monochromatic light used in the experiment, is n. Since the light used in the experiment is monochromatic, in the following we will neglect the effects generated by the phenomenon of light dispersion.

In the time interval Δt_+ in which the light travels the length L of the tube propagating through moving water, the water column in the tube, initially having length L, travels the distance $v \cdot \Delta t_+$, which the light will no longer travel, because it leaves the tube (Fig. 1).

It follows that, from entering the tube to exiting it, the light crosses a column of water of length ($L - v \cdot \Delta t_+$) and refractive index n.

In the following, we will determine, in the laboratory reference system, the length of the optical path traveled by light when it propagates over a distance equal to the length L of the tube, through water moving at a speed $\vec{v}$ relative to it. To do this, we isolate the water column of length ($L - v \cdot \Delta t_+$) and refractive index n from the rest of the water flowing through the tube, and analyze the propagation of light through it.

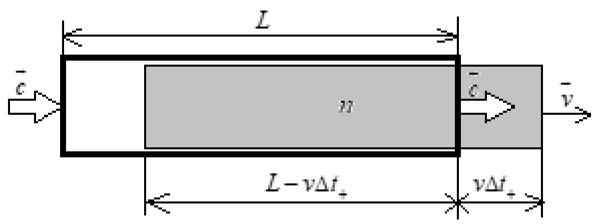

Fig. 1 - The movement through the tube of the water column of length L and refractive index n, in the time interval Δt_+.

We first consider that the water column of length $(L - v\cdot\Delta t_+)$ and refractive index n is at rest in the tube, at position AB (Fig. 2.).

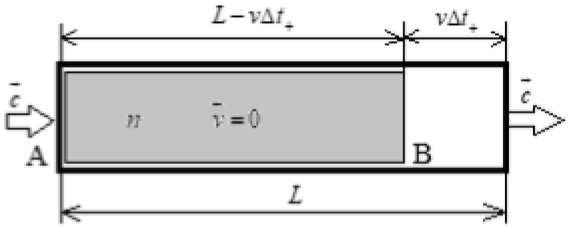

Fig. 2 - Water column of length $L - v\cdot\Delta t_+$ and refractive index n, at rest relative to the tube.

The length of the optical path traveled by light when propagating along the entire length L of the tube, is, in this case:

$$(\Delta x) = (L - v\cdot\Delta t_+)\cdot n + v\cdot\Delta t_+ \qquad (4)$$

But, in the laboratory reference system, light crosses the water column of length $(L - v\cdot\Delta t_+)$ and refractive index n, propagating over a distance L, through a medium having a different refractive index in its propagation direction. We expand the water column of length $(L - v\cdot\Delta t_+)$ and refractive index n, transforming it into a water column of length L and refractive index n' (Fig. 3).

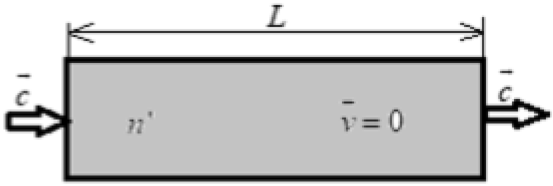

Fig. 3 - Water column of length L and refractive index n', at rest relative to the tube.

The length of the optical path traveled by light as it propagates through the new column of water, at rest in the tube, is:

$$(\Delta x)' = Ln' \quad (5)$$

The refractive index n' can be determined from the condition that the lengths of the optical paths traveled by light, when propagating along the length L of the tube, in the two cases, are equal:

$$(\Delta x) = (\Delta x)' \quad (6)$$

It follows that:

$$(L - v \cdot \Delta t_+)n + v \cdot \Delta t_+ = L \cdot n' \quad (7)$$

Or:

$$Ln - v \cdot \Delta t_+ (n-1) = Ln' \quad (8)$$

Dividing by L in relation (8), we obtain:

$$n' = n - \frac{v \cdot \Delta t_+ \cdot (n-1)}{L} \quad (9)$$

But in the time interval Δt_+, the water column of length $L - v \cdot \Delta t_+$ and refractive index n moves through the tube over a distance $v \cdot \Delta t_+$, passing from position AB to position CD (Figure 4).

The displacement of the water column of length $L - v \cdot \Delta t_+$ and refractive index n is equivalent to the displacement of the water column of length L and refractive index n' over the same distance, the latter moving from position A'B' to position C'D' (Fig. 5).

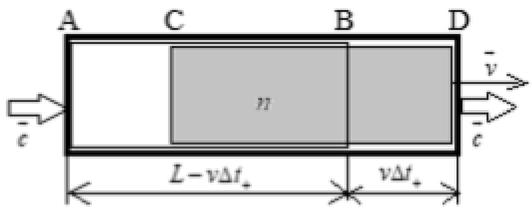

Fig. 4 - The displacement of water column of length $L - v \cdot \Delta t_+$ and refractive index n , in the time interval Δt_+ .

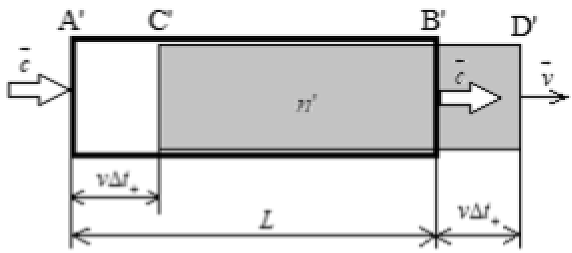

Figure 5: The displacement of the water column of length L and refractive index n' , in the time interval Δt_+ .

The consequence of the displacement of the water column of length L and refractive index n' , over a distance $v \cdot \Delta t_+$, is that the length of the optical path traveled by light, during its propagation from A' to B', increases with $v \cdot \Delta t_+$ (distance A'C', without water) and decreases with $v \cdot n' \cdot \Delta t_+$ (distance B'D', containing water with the refractive index n').

It follows that the total length of the optical path traveled by light in LRS, during its propagation from A' to B' is:

$$(L) = Ln' + v\Delta t_+ - vn'\Delta t_+ = (L - v\Delta t_+)n' + v\Delta t_+ \tag{10}$$

So:

$$(L) = (L - v\Delta t_+)(n - \frac{v\Delta t_+(n-1)}{L}) + v\Delta t_+ \tag{11}$$

That is:

$$(L) = Ln - 2vn\Delta t_+ + 2v\Delta t_+ + \frac{v^2(\Delta t_+)^2(n-1)}{L} \qquad (12)$$

Since Δt_+ is very small, the term $\frac{v^2(\Delta t_+)^2(n-1)}{L}$ can be neglected.

Also, the length of the optical path traveled by light in the time interval Δt_+ can be expressed by the relationship:

$$(L) = c \cdot \Delta t_+ \qquad (13)$$

It follows that:

$$c \cdot \Delta t_+ = Ln - 2v \cdot \Delta t_+(n-1) \qquad (14)$$

Or:

$$Ln = \Delta t_+[c + 2v(n-1)] \qquad (15)$$

In general, the speed of light relative to the reference system in which the measurements are made, that is relative to the LRS, is defined by the ratio between the geometric distance traveled by light in the LRS and the time interval in which that distance is traveled, regardless of its refractive composition.

In the case considered above, the speed of light relative to the LRS, when propagating through a homogeneous optical medium, in the direction of its velocity $\vec{v}$ relative to the LRS, is:

$$c_+ = \frac{L}{\Delta t_+} = \frac{c}{n} + \frac{2v(n-1)}{n} \qquad (16)$$

The refractive index of the optical medium through which light propagates, determined in the laboratory reference system, has, in the considered case, the expression:

$$n_+ = \frac{c}{c_+} = \frac{c}{\frac{c}{n} + \frac{2v(n-1)}{n}} = \frac{cn}{c(1 + \frac{2v(n-1)}{c})} = \frac{n}{1 + \frac{2v(n-1)}{c}} \qquad (17)$$

If light propagates through the optical medium in the opposite direction to its velocity $\vec{v}$, in Eq. (16) the sign of the velocity v will be reversed and, in this case, the speed of light relative to the LRS will be:

$$c_- = \frac{L}{\Delta t_-} = \frac{c}{n} - \frac{2v(n-1)}{n} \tag{18}$$

An analysis of equation (16) would indicate the existence of a new coefficient of light entrainment by the moving optical medium:

$$f' = \frac{2(n-1)}{n} \tag{19}$$

In reality, the increase in the speed of light in the LRS is determined, in the considered case, by the decrease in the number of particles of the medium overcome by light per unit length, a phenomenon which, macroscopically, manifests itself by the decrease in the refractive index of the optical medium through which light propagates in the laboratory reference system.

From equation (16) it follows that if $v = 0$, c_+ becomes c/n, that is the speed of light through the optical medium at rest in the laboratory reference system.

It can also be observed that $c_+ = c$ if $v = \frac{c}{2}$, and this occurs regardless of the refractive index n of the optical medium at rest in the LRS.

In our opinion, this fact could provide important information regarding the interaction of light with matter and even about the nature of light. Obviously, this information could only be obtained if the new formula for the speed of light through a moving optical medium correctly expresses the propagation of light through optical media, that is, whether the predictions based on its use coincide with the experimental results.

4. A VERIFICATION OF THE AGREEMENT BETWEEN THE PREDICTION OF THE "DELAY-TIME" MODEL AND THE RESULTS OF THE FIZEAU'S EXPERIMENT

In 1851, Fizeau performed an experiment whose purpose was to verify to what extent the speed of light through an optical medium moving relative to the LRS, is different from its speed through the same medium, at rest in the LRS.

The method used by Fizeau was a differential one. It was based on measuring the interference effects generated by the appearance of small differences between the propagation speeds of two coherent beams of light, which propagate in opposite directions through a U-shaped tube, through which an optical medium (water) is moving with speed $\vec{v}$. A sketch of the Fizeau experiment is given in Fig. 6.

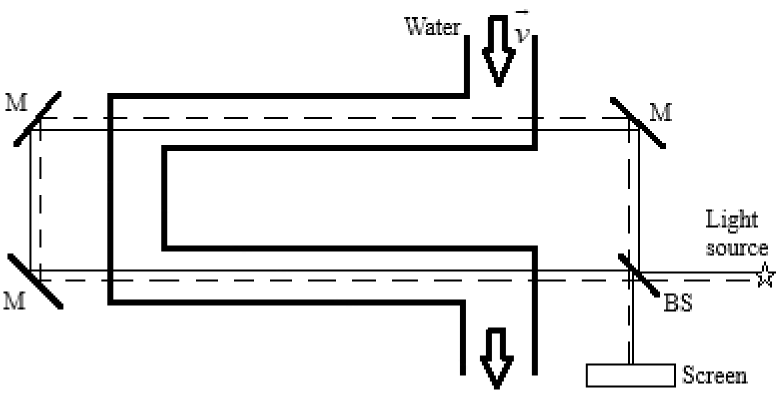

Figure 6: A sketch of Fizeau's experiment. M=mirror and BS=beam splitter.

Fizeau expressed the results of his experiment through a relative quantity, called displacement of the bands or fringe shift (FS):

$$(FS) = \frac{\Delta x}{\beta} \qquad (20)$$

In relation (20), Δx represents the displacement of the interference pattern when water flows through the tube with a velocity v, relative to its position when the water is at rest in the tube, and β is the bandwidth, i.e. the distance between two consecutive interference fringes. Using the usual formulas from the Young experiment ($\beta = \frac{\lambda D}{d}$ and $\Delta x = \frac{c\Delta t \cdot D}{d}$) it follows that the fringe shift (FS) can also be expressed by the relation:

$$(FS) = \frac{c \cdot \Delta t}{\lambda} \qquad (21)$$

In relation (21), Δt represents the difference between the time intervals in which the two light beams travel the length $2L$ of the U-shaped tube, propagating in the opposite direction through it:

$$\Delta t = \Delta t_{-} - \Delta t_{+} = \frac{2L}{\frac{c}{n} - \frac{2v(n-1)}{n}} - \frac{2L}{\frac{c}{n} + \frac{2v(n-1)}{n}} = \frac{8Lvn(n-1)}{c^2 - 4v^2(n-1)^2} \qquad (22)$$

Because $4v^2(n-1)^2 \ll c^2$, we can neglect the term $4v^2(n-1)^2$. It follows that:

$$\Delta t = \frac{8Lvn(n-1)}{c^2} \qquad (23)$$

By introducing Eq. (23) into Eq. (21) we obtain the expression of the theoretical prediction of the fringe shift, according to the delay-time model:

$$(FS)_{delay} = \frac{8Lvn(n-1)}{\lambda c} \qquad (24)$$

The average value of the displacements of the interference fringes measured by Fizeau was:

$$(FS)_{\exp} = 0.23016 \qquad (25)$$

By introducing into Eq. (24) the values of the physical quantities used in the Fizeau experiment ($L = 1.487m$, $n = 1.33$, $v = 7.059m/s$ and $\lambda = 526 \cdot 10^{-9} m$), we obtain:

$$(FS)_{delay} = 0.2335 \qquad (26)$$

Comparing the two values, it is found that the theoretical prediction of the “delay-time” model verifies the results of the Fizeau experiment very well.

We specify that the theoretical prediction offered by the theoretical models through which Fresnel's formula is reached, to explain the results of the Fizeau experiment [7], is:

$$(FS)_{Fresnel} = \frac{4Lv(n^2-1)}{\lambda c} = 0.2022 \qquad (27)$$

It should be noted, however, that the almost perfect coincidence between the prediction of the “delay-time” model and the results of the Fizeau experiment only occurs if in the relation (24) the velocity v is the average velocity of the water through the tube. If in relation (24) the velocity v is replaced by the velocity of the water through the center of the tube, estimated by Michelson and Morley to be 1.165 times greater than the average velocity of the water through the tube [12], the prediction of the “delay-time” model deviates by about 18% from the experimental results.

However, in our opinion, it is possible that the water velocity through the center of the tube has a value very close to the value of the average water velocity through the tube, because the water flow through the Fizeau experiment tube is totally turbulent and, in this case, it was not possible to theoretically determine the distribution of water velocities through the cross-section of the tube. It should also be noted that the experiment by which Michelson and Morley determined the distribution of water velocities as a function of the distance from the center of the tube was mechanically invasive, and therefore unreliable.

5. CONCLUSIONS

The results of Fizeau's 1851 experiment showed that the speed of light through an optical medium, depends on the velocity v of that medium relative to the LRS, in a way different from that established in Galilean mechanics.

Fresnel's formula, initially deduced by him within the framework of the partially entrained ether model and later by other scientists within other physical models, both classical and relativistic, was, for a long time, the only formula with which the results of Fizeau-type experiments were properly explained.

In a paper published in 2025 [1], a new physical model for the propagation of light through an optical medium, called the “delay-time” model, was established. In it, a new formula for the speed of light through a moving optical medium was derived, based on the determination, in the LRS, of the length of the optical path traveled by light when propagating over a distance L, from the LRS, through the respective optical medium, moving with velocity v relative to it. In this paper, the new formula for the propagation of light through a moving optical medium was derived using a method similar to that used in [1], but this time the length of the optical path traveled by light was determined taking into account the change, relative to the LRS, of the refractive index of the optical medium along its direction of motion. According to the delay-time model, the cause of the change in the refractive index is the change in the number of particles per unit length that light overcomes in its direction of propagation.

An analysis of relation (16) shows that, on the one hand, the prediction obtained based on it verifies very well the results of Fizeau-type experiments and, on the other hand, that its derivation within a new theory that would take into account the interaction, at a microscopic level, between a photon and the particles of the optical medium through which it propagates, could provide new information on the nature and propagation of light.

Obviously, the new formula for the speed of light through a moving optical medium can only be considered authentic after careful experimental verification. Therefore, to obtain reliable and indisputable experimental results, it would be necessary to repeat the Fizeau experiment under very well-controlled conditions, offered by new technological facilities.

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