= Fizeau experiment =

The Fizeau experiment was carried out by Hippolyte Fizeau in 1851 to measure the relative speeds of light in moving water . Fizeau used a special interferometer arrangement to measure the effect of movement of a medium upon the speed of light .

According to the theories prevailing at the time , light traveling through a moving medium would be dragged along by the medium , so that the measured speed of the light would be a simple sum of its speed through the medium plus the speed of the medium . Fizeau indeed detected a dragging effect , but the magnitude of the effect that he observed was far lower than expected . His results seemingly supported the partial aether @-@ drag hypothesis of Fresnel , a situation that was disconcerting to most physicists . Over half a century passed before a satisfactory explanation of Fizeau 's unexpected measurement was developed with the advent of Albert Einstein 's theory of special relativity . Einstein later pointed out the importance of the experiment for special relativity .

Although it is referred to as the Fizeau experiment , Fizeau was an active experimenter who carried out a wide variety of different experiments involving measuring the speed of light in various situations .

= = Experimental setup = =

A light ray emanating from the source S ? is reflected by a beam splitter G and is collimated into a parallel beam by lens L. After passing the slits O1 and O2 , two rays of light travel through the tubes A1 and A2 , through which water is streaming back and forth as shown by the arrows . The rays reflect off a mirror m at the focus of lens L ? , so that one ray always propagates in the same direction as the water stream , and the other ray opposite to the direction of the water stream . After passing back and forth through the tubes , both rays unite at S , where they produce interference fringes that can be visualized through the illustrated eyepiece . The interference pattern can be analyzed to determine the speed of light traveling along each leg of the tube .

= = Fresnel drag coefficient = =

Assume that water flows in the pipes with speed v. According to the non @-@ relativistic theory of the luminiferous aether , the speed of light should be increased when " dragged " along by the water , and decreased when " overcoming " the resistance of the water . The overall speed of a beam of light should be a simple additive sum of its speed through the water plus the speed of the water .

That is , if n is the index of refraction of water , so that c / n is the velocity of light in stationary water , then the predicted speed of light w in one arm would be

<formula>

and the predicted speed in the other arm would be

<formula>

Hence light traveling against the flow of water should be slower than light traveling with the flow of water .

The interference pattern between the two beams when the light is recombined at the observer depends upon the transit times over the two paths , and can be used to calculate the speed of light as a function of the speed of the water .

Fizeau found that

<formula>

In other words , light appeared to be dragged by the water , but the magnitude of the dragging was much lower than expected .

The Fizeau experiment forced physicists to accept the empirical validity of an old , theoretically unsatisfactory theory of Augustin @-@ Jean Fresnel (1818) that had been invoked to explain an 1810 experiment by Arago , namely , that a medium moving through the stationary aether drags light propagating through it with only a fraction of the medium 's speed , with a dragging coefficient f given by

<formula>
In 1895 , Hendrik Lorentz predicted the existence of an extra term due to dispersion :
<formula>

= = Repetitions = =

Albert A. Michelson and Edward W. Morley (1886) repeated Fizeau 's experiment with improved accuracy , addressing several concerns with Fizeau 's original experiment : (1) Deformation of the optical components in Fizeau 's apparatus could cause artifactual fringe displacement ; (2) observations were rushed , since the pressurized flow of water lasted only a short time ; (3) the laminar flow profile of water flowing through Fizeau 's small diameter tubes meant that only their central portions were available , resulting in faint fringes ; (4) there were uncertainties in Fizeau 's determination of flow rate across the diameter of the tubes . Michelson redesigned Fizeau 's apparatus with larger diameter tubes and a large reservoir providing three minutes of steady water flow . His common path interferometer design provided automatic compensation of path length , so that white light fringes were visible at once as soon as the optical elements were aligned . Topologically , the light path was that of a Sagnac interferometer with an even number of reflections in each light path . This offered extremely stable fringes superior to those from Fizeau 's design (which used an odd number of reflections) that were , to first order , completely insensitive to any movement of its optical components . The stability was such that it was possible for him to insert a glass plate at h or even to hold a lighted match in the light path without displacing the center of the fringe system . Using this apparatus , Michelson and Morley were able to completely confirm Fizeau 's results .

Other experiments were conducted by Pieter Zeeman in 1914 ? 1915 . Using a scaled @-@ up version of Michelson 's apparatus connected directly to Amsterdam 's main water conduit , Zeeman was able to perform extended measurements using monochromatic light ranging from violet (4358 Å) through red (6870 Å) to confirm Lorentz 's modified coefficient . In 1910 , Franz Harress used a rotating device and overall confirmed Fresnel 's dragging coefficient . However , he additionally found a " systematic bias " in the data , which later turned out to be the Sagnac effect .

Since then , many experiments have been conducted measuring such dragging coefficients , often in combination with the Sagnac effect . For instance , in experiments using ring lasers together with rotating disks , or in neutron interferometric experiments . Also a transverse dragging effect was observed , i.e. when the medium is moving at right angles to the direction of the incident light .

= = Hoek experiment = =

An indirect confirmation of Fresnel 's dragging coefficient was provided by Martin Hoek (1868) . His apparatus was similar to Fizeau 's , though in his version only one arm contained an area filled with resting water , while the other arm was in the air . As seen by an observer resting in the aether , Earth and hence the water is in motion . So the following travel times of two light rays traveling in opposite directions were calculated by Hoek (neglecting the transverse direction , see image) :

The travel times are not the same , which should be indicated by an interference shift . However , if Fresnel 's dragging coefficient is applied to the water in the aether frame , the travel time difference (to first order in v / c) vanishes . Using different setups Hoek actually obtained a null result , confirming Fresnel 's dragging coefficient . (For a similar experiment refuting the possibility of shielding the aether wind , see Hammar experiment) .

In the particular version of the experiment shown here , Hoek used a prism P to disperse light from a slit into a spectrum which passed through a collimator C before entering the apparatus . With the apparatus oriented parallel to the hypothetical aether wind , Hoek expected the light in one circuit to be retarded 7 / 600 mm with respect to the other . Where this retardation represented an integral number of wavelengths , he expected to see constructive interference ; where this retardation represented a half @-@ integral number of wavelengths , he expected to see destructive interference . In the absence of dragging , his expectation was for the observed spectrum to be

continuous with the apparatus oriented transversely to the aether wind , and to be banded with the apparatus oriented parallel to the aether wind . His actual experimental results were completely negative .

= = Controversy = =

Although Fresnel 's hypothesis was empirically successful in explaining Fizeau 's results , many leading experts in the field , including Fizeau himself (1851) , Éleuthère Mascart (1872) , Ketteler (1873) , Veltmann (1873) , and Lorentz (1886) were united in considering Fresnel 's partial aether @-@ dragging hypothesis to be on shaky theoretical grounds . For example , Veltmann (1870) demonstrated that Fresnel 's formula implies that the aether would have to be dragged by different amounts for different colors of light , since the index of refraction depends on wavelength ; Mascart (1872) demonstrated a similar result for polarized light traveling through a birefringent medium . In other words , the aether must be capable of sustaining different motions at the same time .

Fizeau 's dissatisfaction with the result of his own experiment is easily discerned in the conclusion to his report :

The success of the experiment seems to me to render the adoption of Fresnel 's hypothesis necessary , or at least the law which he found for the expression of the alteration of the velocity of light by the effect of motion of a body ; for although that law being found true may be a very strong proof in favour of the hypothesis of which it is only a consequence , perhaps the conception of Fresnel may appear so extraordinary , and in some respects so difficult , to admit , that other proofs and a profound examination on the part of geometricians will still be necessary before adopting it as an expression of the real facts of the case .

Despite the dissatisfaction of most physicists with Fresnel 's partial aether @-@ dragging hypothesis , repetitions and improvements to his experiment (see sections above) by others confirmed his results to high accuracy .

Besides the problems of the partial aether @-@ dragging hypothesis , another major problem arose with the Michelson ? Morley experiment (1887) . In Fresnel 's theory , the aether is almost stationary , so the experiment should have given a positive result . However , the result of this experiment was negative . Thus from the viewpoint of the aether models at that time , the experimental situation was contradictory : On one hand , the aberration of light , the Fizeau experiment and the repetition by Michelson and Morley in 1886 appeared to support partial aether @-@ dragging . On the other hand , the Michelson ? Morley experiment of 1887 appeared to prove that the aether is at rest with respect to Earth , apparently supporting the idea of complete aether @-@ dragging (see aether drag hypothesis) . So the very success of Fresnel 's hypothesis in explaining Fizeau 's results helped lead to a theoretical crisis , which was not resolved until the development of the theory of special relativity .

= = Lorentz 's interpretation = =

In 1892 , Hendrik Lorentz proposed a modification of Fresnel 's model , in which the aether is completely stationary . He succeeded in deriving Fresnel 's dragging coefficient as the result of an interaction between the moving water with an undragged aether . He also discovered that the transition from one to another reference frame could be simplified by using an auxiliary time variable which he called local time :

<formula>

In 1895 , Lorentz more generally explained Fresnel 's coefficient based on the concept of local time . However , Lorentz 's theory had the same fundamental problem as Fresnel 's : a stationary aether contradicted the Michelson ? Morley experiment . So in 1892 Lorentz proposed that moving bodies contract in the direction of motion (FitzGerald @-@ Lorentz contraction hypothesis , since George FitzGerald had already arrived in 1889 at this conclusion) . The equations that he used to describe these effects were further developed by him until 1904 . These are now called the Lorentz transformations in his honor , and are identical in form to the equations that Einstein was later to

derive from first principles . Unlike Einstein 's equations , however , Lorentz 's transformations were strictly ad hoc , their only justification being that they seemed to work .

= = Derivation in special relativity = =

Einstein showed how Lorentz 's equations could be derived as the logical outcome of a set of two simple starting postulates . In addition Einstein recognized that the stationary aether concept has no place in special relativity , and that the Lorentz transformation concerns the nature of space and time . Together with the moving magnet and conductor problem , the negative aether drift experiments , and the aberration of light , the Fizeau experiment was one of the key experimental results that shaped Einstein 's thinking about relativity . Robert S. Shankland reported some conversations with Einstein , in which Einstein emphasized the importance of the Fizeau experiment :

He continued to say the experimental results which had influenced him most were the observations of stellar aberration and Fizeau 's measurements on the speed of light in moving water . " They were enough , " he said .

Max von Laue (1907) demonstrated that the Fresnel drag coefficient can be easily explained as a natural consequence of the relativistic formula for addition of velocities , namely :

The speed of light in immobile water is c / n .

From the velocity composition law it follows that the speed of light observed in the laboratory , where water is flowing with speed v (in the same direction as light) is

<formula>

Thus the difference in speed is (assuming v is small comparing to c , dropping higher order terms)

<formula> <formula>

This is accurate when v / c ? 1 , and agrees with the formula based upon Fizeau 's measurements , which satisfied the condition v / c ? 1 .

Fizeau 's experiment is hence supporting evidence for the collinear case of Einstein 's velocity addition formula .