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Fresnel's (Dragging) Coefficient as a Challenge to 19th Century Optics of Moving Bodies

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1.1 Introduction

It has been suggested that, during the latter half of the 19th century up to about 1890, the optics of moving bodies was considered to be a more-or-less unproblematic branch of physics. In view of the continuing success of Fresnel's formula for the dragging coefficient (hereafter called Fresnel's coefficient) in explaining all new experimental optical data to order v/c, "There were simply no major problems to solve here, or so it was generally thought" (Buchwald 1988, 57).

These words are the summation of the following quotation: "In 1851 Armand Fizeau was able to measure the Fresnel "drag" coefficient, and in 1873 Wilhelm Veltmann demonstrated that no optical experiment with a terrestrial source of light can, to first order, detect motion through the ether if the drag coefficient obtains. Consequently, to this degree of accuracy, Fresnel's original theory which requires a very slight transport of the ether by transparent bodies was quite satisfactory (ibid.)"

(Schaffner 1972) includes a similar comment: "...Fresnel was able to formulate a simple and elegant explanation of Arago's results on the basis of the wave theory of light; an explanation which not only accounted for aberration effects then known but which was subsequently confirmed in a number of ways throughout the nineteenth century (ibid., 24)."

As we shall see, both Buchwald and Schaffner conflate the continued empirical success of Fresnel's formula with the ultimately unsuccessful attempts by Fresnel and others to find a satisfactory theoretical explanation of the formula. I maintain that:

1) On the basis of contemporary documentation, one can demonstrate that, by the first decades of the second half of the 19th century, that is before the Michelson and Michelson–Morley experiments, the empirical success of Fresnel's formula in explaining all first-order experiments actually created a critical situation within the optics of moving bodies.[1]
2) The challenge presented by Fresnel's formula was the first indication of the breakdown of classical (Galilei–Newtonian) kinematics, and could have led directly to the search for a new kinematics.

3) The way in which the challenge of this first crisis was met by Lorentz, on the basis of Maxwell's electrodynamics, the stationary ether hypothesis, and the old kinematics exerted a tranquilizing influence that served to postpone the search for a new kinematics until a new critical situation in the electrodynamics of moving bodies arose, largely due to the results of the second-order M-M experiments, and was resolved in 1905 by Einstein.

1.2 Arago and the Emission Theory

Although the story is mainly concerned with the wave theory of light, I shall start it with Dominique-François Arago's work on the emission theory. In 1810, Arago, still an adherent of this theory, decided to test a hypothesis that seemed to him "both natural and probable on its basis," namely that "stars of differing magnitude can emit [light] rays with different speeds."

Arago's test of this hypothesis was based on the refraction of these rays by a prism, and he found that, to the accuracy of his experiment, rays from all stars were refracted by the same angle. He concluded that "light moves with the same speed no matter what the body from which it emanates." He regarded this conclusion as so important that he later cited it (Arago 1830) as one of the main reasons why "the emission theory now has very few partisans." Indeed, "Arago became a vocal critic of the Newtonian emission theory and, by 1816, an ardent supporter of the undulatory theory" (Hahn 1970, 201).

Arago noted that his conclusion, viz. that the speed of light is independent of the speed of its source, depends on what he called "Newton's principle:" Light beams entering a prism with different speeds are refracted through different angles; and he decided to test this principle. Again he used a prism, but while his earlier experiment had compared light from different stars at the same time, he now used the prism to compare light from the same star at different times of the year. Since the earth moves around the sun during the course of a year, he expected the velocity of light relative to the prism to change and hence, on the basis of "Newton's principle," the angle of refraction to change. But he found, as Fresnel 1818 summarized Arago's results, "that the motion of the terrestrial globe has no noticeable influence on the refraction of rays that emanate from the stars." The situation is summarized in the following table:

Arago's Experiments—Is the Null Result a Problem for:

Starlight refracted by:	Emission Theory	Wave Theory-Stationary Ether
1. Different Stars-Same Time	Yes	No
2. Same Star-Different Times	Yes	Yes

Table 1.1. Emission vs. Wave Theory

On the basis of the emission theory, Arago could only explain this new result by invoking what Fresnel called a "quite strange hypothesis that is quite difficult to accept" (viz., while light travels at many different velocities, the eye is sensitive only to rays traveling at one speed). Having become well acquainted with Fresnel's work on the wave theory by the mid 1810s, Arago asked the latter if the wave theory could provide an explanation. Fresnel now attempted to explain both aberration and Arago's second prism experiment (the wave-theoretical explanation of the first is obvious, as we shall see below).

1.3 Fresnel and the Wave Theory

Fresnel's work on the wave theory was based on the hypothesis of a stationary or immobile ether. On this basis, the explanation of Arago's first experiment is obvious: the speed of propagation of a wave in a medium is independent of the velocity of the source of the wave. The explanation of aberration in a vacuum is also fairly simple (for details, see, e.g., Janssen and Stachel 1999). But two results:

1) that the angle of aberration remains the same in a telescope using lenses or even filled with water;

2) the null result of Arago's second experiment cannot be explained without an additional hypothesis attributing some mobility to the ether within a moving medium. Fresnel showed that both of these results can be explained on the assumption that a medium moving through the stationary ether only drags light propagating through it with a fraction of the medium's speed. If the index of refraction of the medium at rest is n, then Fresnel defined the dragging coefficient

$$f = (1 - 1/n^2)$$

and assumed that light propagating in the medium is dragged along with a velocity

$$v_{\text{drag}} = f v_{\text{med}}.$$

What the dragging coefficient accomplishes is summarized in the following Table:

Wave Theory: Stationary Ether	
Without Dragging Coeff.	With Dragging Coeff.
ABERRATION WITH OPTICAL MEDIUM	
Problem	No Problem
ARAGO'S EXPERIMENT	
Problem	No Problem

Table 1.2. Why Fresnel needs f

What physical explanation does Fresnel offer for the value of the dragging coefficient?

> [I]t is only a part of this medium [the ether] which is carried along by our earth, namely that portion which constitutes the excess of its density over that of the surrounding ether. By analogy it would seem that, when only a part of the medium is displaced, the velocity of propagation of the waves can only be increased by the velocity of the center of gravity of the system (Fresnel 1818a, 631; translation from Schaffner 1972, 129, translation modified).

Since the speed of a wave in a medium depends on both the density of the medium and (inversely) on the elasticity of the medium, Fresnel's explanation amounts to assuming that the elasticity remains the same in the prism and the ether and that only the density varies between them. In a note later added to the letter, he admits that other hypotheses regarding the elasticity are equally possible, but adds:

> But whatever the hypothesis one makes concerning the causes of the slowing of light when it passes through transparent bodies, one may always ... mentally substitute for the real medium of the prism, an elastic fluid with the same tension as the surrounding ether, and having a density such that the velocity of light is precisely the same in this fluid and in the prism, when they are supposed at rest; this equality must still continue to hold in these two media when carried along by the earth's motion; these, then, are the bases upon which my calculation rests (Fresnel 1818b, 836; translation from Schaffner 1972, 134–135, translation modified).

This is the first, but hardly the last time that we shall come upon a disturbing problem: the lack of uniqueness in explanations of Fresnel's coefficient. It has been suggested, notably by Veltmann (see below), that Fresnel first found the value of the coefficient that explained the anomalous experimental results, and then cooked up a theoretical explanation for this value.

During the course of the nineteenth century, various hypotheses about the motion of the ether were introduced to derive the value of f. Even if one assumes that only the density of the ether varies from medium to medium, various possibilities about its state of motion inside a moving body were proposed, all cooked up to lead to the same value of f. To cite only three:

1) A part of the ether moves with the total velocity of the moving body (Fresnel 1818a).

2) All of the ether is dragged along with a part of the velocity of the moving body (Stokes 1846).

3) Various portions of the ether move with all velocities between zero and the total velocity of the moving body (Beer 1855).

The very fact that such widely differing hypotheses could be invoked to explain equally well the value of f raises a good deal of doubt about all such "mechanical ether" explanations.

Wave Theory: Ether is:	
Stationary (Fresnel)	Dragged-Along (Stokes)
ABERRATION-Empty Space	
No Problem	Problem but Stokes Solves It
ARAGO'S 2nd EXPERIMENT	
Problem—f needed	No Problem—f not needed

Table 1.3. Stokes vs. Fresnel

1.4 Stokes Saves the Dragged-Along Ether

Of course, life would be much simpler if one could just assume that the ether is dragged along entirely by a moving body. Fresnel realized this, but remarks that he cannot think of a mechanism that would then explain aberration In Stokes 1845, such an explanation is offered. Without going into detail about Stokes's explanation, suffice it to say that there is a striking difference between his explanation and earlier ones. For Stokes, aberration involves a real bending of light beams as they pass from empty-space ether into a moving medium, which even an observer at rest would see; while both for the corpuscular and immobile-ether wave theories, aberration is a sort of optical illusion, apparent only to a moving observer. Stokes theory had a curious history over the next half-century (see (Janssen and Stachel 1999) for a bit of the story), but its attractiveness was immediately apparent, and the question was soon raised: Who needs Fresnel's dragging coefficient? As the following table shows, it seems that nobody did. Two equally good hypotheses about the relation between the ether and ponderable matter immobility with Fresnel's coefficient and total dragging without it both seemed available to explain all the known experimental facts in the optics of moving bodies.

Stokes commented:

> This affords a curious instance of two totally different theories running parallel to each other in the explanation of phenomena. I do not suppose many would be disposed to maintain Fresnel's theory, when it is shewn that it may be dispensed with, inasmuch as we would not be disposed to believe, without good evidence, that the ether moved quite freely through the solid mass of the earth. Still, it would have been satisfactory, if it had been possible, to have put the two theories to the test of some decisive experiment (Stokes 1846, 147).

1.5 Fizeau Forces Fresnel's Formula on Physicists

So things stood until 1850, when an apparently decisive experiment was performed. As Ketteler 1873 (a historical review) reports:

> [S]uddenly (1850) Fizeau's famous experiment, by means of which the "entrainment" of the ether by a moving transparent medium was actually proved, brought light into this chaos, and now Fresnel's viewpoint gained a firmer foundation and with it new adherents.

Fizeau 1851 reports the results of this experiment, which was taken to demonstrate conclusively the need for f. He measured the speed of light in a moving optical medium, water in his case (see, e.g., (Janssen and Stachel 1999) for a discussion), by splitting a beam of light into two beams, one of which traveled through a tube of running water in the sense of the water's motion, the other in the opposite sense. His results may be summarized as follows. Let

$$\begin{aligned} c_{\text{med}} &= c/n = \text{the speed of light w.r.t the medium,} \\ v_{\text{lab}} &= \text{the speed of the medium w.r.t the laboratory,} \\ c_{\text{lab}} &= \text{the speed of light w.r.t. the laboratory.} \end{aligned}$$

From interference effects between the two beams, Fizeau drew the conclusion that:

$$c_{\text{lab}} = c_{\text{med}} \pm f v_{\text{lab}},$$

the sign depending on whether the water is flowing in the same or opposite direction to that of the light propagation.

Now, even adherents of Stokes' theory needed to invoke f to explain Fizeau's results. The dragging coefficient seemed unavoidable! Stationary ether theories once again became the favored ones—"stationary" being interpreted to include dragging effects in moving media, of course.

1.6 Formula Yes! Explanation No!

In spite of its empirical validation, many leading experts in the field, starting with Fizeau himself, and including Ketteler, Veltmann, Mascart, Poincaré, Potier and Lorentz (all before 1890), carefully distinguished between the empirical success of the formula and the dubious nature of Fresnel's—and all other—explanations based on the motion of the ether, in whole or in part. Here are some representative samples:

Fizeau (1851): The success of this experiment seems to me to entail the adoption of Fresnel's hypothesis, or at least of the law that he found to express the change in the speed of light resulting from the motion of bodies; for although this law has been verified ... Fresnel's conception would appear so extraordinary, and in several respects so difficult to accept, that one would require still more proofs and a deepened examination by mathematical physicists [géomètres], before accepting it as the expression of the way things really are.

Ketteler (1873): That indeed the speed of propagation of light undergoes a modification corresponding to Fresnel's theory as a result of translation [of the medium] has been experimentally confirmed by Fizeau's experiments with moving fluids. It is one thing to simply acknowledge this modification, another to accept Fresnel's conception of the way in which it comes about.

Veltmann (1873): Fresnel sought to bring this result [i.e., Arago's] into harmony with the wave theory, saw himself thereby compelled to adopt a particular hypothesis, that indeed, as concerns its physical basis, itself again offered insurmountable difficulties, yet for the rest accomplished its aim.

Mascart (1872): In any case, to be rigorous, it must be stated that Fizeau's experiment only verified that the dragging of the [light] waves by moving media is in agreement with [Fresnel's] formula (1) and that one can replace Fresnel's hypothesis by any other hypothesis that will finally lead to the same formula, or a slightly different one.

Mascart (1893): The considerations that guided Fresnel are insufficient; the formula to which he was led by a happy intuition only has an empirical character, which should be interpreted by theory.

Poincaré (1889): We do not know any satisfactory theory to justify that hypothesis [i.e., a hypothesis that would lead to Fresnel's formula].

Lorentz (1886): It will be the task of the theory of light to explain [rendre compte] the value that observations give for the dragging coefficient.

1.7 Further Empirical Success Brings Increasing Theoretical Doubt

Indeed, the very empirical successes of Fresnel's formula made ever more evident the inadequacy of all explanations of it based on partial or total dragging of the ether inside a moving optically transparent body. Two further results made this crystal clear:

1) Veltmann (1870) demonstrates experimentally that Fresnel's formula must be applied using the appropriate (different) index of refraction for each color of light. This means that, however the ether moves, it must move differently for each frequency of light. But what happens when white light (or indeed any mixture of frequencies) passes through a transparent medium.

2) (Mascart 1872, 1874) demonstrate that, in a birefringent medium, the differing indices of refraction for the normal and extraordinary rays must be used in applying Fresnel's formula. Again, if an explanation of Fresnel's coefficient in terms of a moving ether is given, then in a birefringent medium the ether must be capable of sustaining two different motions at the same time.

But if there was no further progress in explaining Fresnel's formula between 1850 and 1880, there was great progress in understanding its theoretical implications.

1.8 From Compensation to Relative Motion

As we have seen, Fresnel originally introduced f to explain the absence of expected effects of the earth's motion through the ether. This mutual cancellation of effects that, by themselves, would produce evidence of this motion came to be referred to as “compensation” (the first use of this term that I have found is in Fizeau 1851) of the expected effects of this motion, which combined to produce a total null effect in each special case.

Veltmann (1870) introduced a new viewpoint that transcends the use “of this hypothesis [i.e., Fresnel’s formula] . . . for the explanation of one or another special observation and indeed always by means of a so-called compensation.” [In the 1873 version, he was more explicit: “a compensation of various . . . changes in the direction of the wave normals from those that had been demonstrated at rest.”]

“This viewpoint is simply that of relative motion... Fresnel’s hypothesis is thus nothing more than the necessary and sufficient condition for the applicability of the laws that follow from the wave theory for the refraction of the rays in media at rest to the relative rays in moving media.”

Veltmann argues that Fresnel actually arrived at his formula by realizing it was needed to explain Arago’s results. “The considerations by mean of which Fresnel attempted to give [his formula] a physical foundation are worthless and therefore remain unconsidered here” (1873).

In order to explain interference phenomena (such as the results of Fizeau’s experiment), Veltmann showed that Fresnel’s formula can be used to prove the following theorem:

> “In order to traverse a closed polygon, light always requires the same time, whether the medium be at rest or has any parallel motion that is very small in comparison to the speed of light” (1873).

Around this time, Mascart (1874) formulated what we may call the optical principle of relativity: “The translational motion of the earth has no appreciable influence on optical phenomena produced by a terrestrial source, or by light from the sun; these phenomena do not provide us with a means of determining the absolute motion of a body, and relative motions are the only ones we are able to determine.”

1.9 Potier and Time

Potier (1874) gives a reinterpretation of Fresnel’s formula that rids it of its dependence on the index of refraction by emphasizing the time intervals involved in the transmission of light. He showed that:

> If a body is in motion, the time that light takes to travel the distance l between two points A and B belonging to the body is increased by lu/V^2 by virtue of the motion, u being the component of the velocity of the body in the direction of the line AB, V being the speed of propagation of light in vacuum (1874).

While he had only shown his result to follow from Fresnel’s formula by neglecting terms of order $(u/V)^2$, he pointed out that his result “alone would rigorously provide the explanation of the observed phenomena,” and suggests that “for speeds comparable to the speed of light . . . Fresnel’s law, exact for small speeds, could thus be supplemented by this purely empirical statement” (1874).

1.10 The Local Time

(Poincaré 1905) is an obituary of Potier, who had been one of Poincaré's teachers. In it, he commented on Potier's work on optics of moving bodies:

> Aberration and Fizeau's experiments show us that the ether is not carried along by matter; how does it happen then that this relative motion of the ether and the earth cannot be demonstrated by any optical experiment? Potier made a considerable step forward in answering this question; and it was necessary to wait for Lorentz before a new step was taken that has brought us so close to the solution that we are almost touching it.

What did Poincaré consider to be Potier's "considerable step forward?" He does not say explicitly, but I believe that it was a step towards the concept of what Lorentz later named "the local time," a concept which Poincaré was the first to give a physical interpretation.

Let me try to justify this claim. Let:

$\Delta t =$ the time interval for light to travel between the points A and B in some optical medium at rest,

$\Delta x = l$ be the distance between points $A$and B,

$\Delta t' =$ the time interval for light to travel between A and B when the medium is moving with velocity u.

In this notation, Potier's formula becomes:

$$\Delta t' = \Delta t + (u.\Delta x)/V^2,$$

or

$$\Delta t = \Delta t' - (u.\Delta x)/V^2,$$

where V is the velocity of light in vacuum. We see at once that, formally, this is the same as Lorentz' (1895) expression for the local time.

1.11 Comments On This Result and Some Speculations

1) Since the medium is arbitrary, by varying its index of refraction n the velocity of light in the medium can (in principle) be made to vary between 0 and V:

$$V_{\text{med}} = V/n, \quad n \geq 1.$$

So the time interval $\Delta t = l/V_{\text{med}}$ can assume any value that makes the events at A and B causally connectible (i.e., in special-relativistic language, that keeps the space-time interval between them timelike or null).

2) Suppose we make the assumption that Δt, the time interval between two events at A and B when the medium is at rest, is always the time interval between these events as measured in a frame of reference in which the medium is at rest, even when the medium is in motion [Note that, if we do not make this assumption, it follows that a simple time measurement could detect the earth's motion through the ether.]

We thereby give a physical interpretation of the local time that implies that the time interval between a pair of events depends on the frame of reference in which it is measured, and hence the need for a non-Galilei–Newtonian kinematics.

3) Newton–Galilean kinematics would yield:

$$\Delta x' = \Delta x + u.\Delta t'.$$

If one were to introduce a modified Newton–Galilean formula:

$$\Delta x' = \Delta x + u.\Delta t,$$

then even without any calculation, it is easy to see that the exact relativistic law of addition of velocities would follow from the equations for $\Delta t'$ and $\Delta x'$: both lack the factor, so their quotient will be exactly the same as if the factor were there!

4) I have no evidence that, in introducing the local time as a formal mathematical device, Lorentz was influenced by Potier's work; but Poincaré's comment cited above makes it seem likely that Poincaré was influenced by Potier in first giving a physical interpretation to Lorentz's local time:

"If one starts to consider seriously the idea that the time interval between two events at different places might be different when measured in different frames of reference, one is led to reflect on the need to synchronize clocks at rest in each frame in order to measure such time intervals" (Poincaré 1898).

Poincaré was the first to interpret the local time as the time that clocks would read in a moving frame if light rays were used to synchronize them on the assumption that the (vacuum) velocity of light is V, even relative to the moving frame (Poincaré 1900).

5) Lorentz's (1892) success in deriving Fresnel's coefficient on the basis of Maxwell's equations and the hypothesis of a stationary ether served to divert attention from the kinematic aspects of the problem. He soon (1895) gave a simplified derivation, based on the concept of the local time, that did not explicitly involve electromagnetic theory; but by that time the close association between Fresnel's coefficient and Maxwell's theory seems to have been taken for granted.

6) Even Einstein was still so much under the spell of Lorentz's interpretation that he failed to notice the kinematic nature of Fresnel's formula, resulting from direct application of the relativistic law of combination of relative velocities; it was left for Laue to make this observation in 1907.

Is it fantastic to imagine that someone might have been led to develop some or all of these kinematical responses to the challenge presented by the situation in the optics of moving bodies around 1880, given that an optical principle of relative motion had been formulated by Mascart? Perhaps no more fantastic than what actually happened: Einstein's development around 1905 of a kinematical response to the challenge presented by the situation in the electrodynamics of moving bodies, given that an electrodynamic principle of relative motion had already been formulated by Poincaré.

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Notes

[1] By "critical situation," I mean a feeling expressed by an important segment of the physics community that something is amiss in their field of expertise: a mismatch between either experimental results and theoretical explanations, as in the two critical situations mentioned here; or between the accounts offered by different theories in some area, in which both should be applicable, as in the current critical situation in the field of quantum gravity.